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Designing a new national forest survey for Sweden

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to estimate these parameters or to use fixed values, which are determined from earlier experience, of the weights a_1, a_2 and a_3. This is possible since the variance of y_4, say, as a function of a_1, a_2 and a_3 is rather flat in a neighbourhood of the optimal values. Thus small (or moderate) deviations from the optimal values only increase the variance by very little.

In the random approach the average volume year i is given by

$$\bar{X}(i) = \int_Q X(s,i)\,ds/|Q|,$$

where $|Q|$ is the area of the region Q and $X(s,i)$ is a stochastic process. Let

$$\bar{X} = \begin{bmatrix} \bar{X}(1) \\ \bar{X}(2) \\ \bar{X}(3) \\ \bar{X}(4) \end{bmatrix}$$

and denote the expectation, $E(\bar{X})$, of $\bar{X}$ by

$$\mu = \begin{bmatrix} \mu(1) \\ \mu(2) \\ \mu(3) \\ \mu(4) \end{bmatrix}$$

In the estimation procedure we shall utilize the dependence between $\bar{X}(i)$ and $\bar{X}(j)$. If the correlation between $X(s,i)$ and $X(s,i-2)$ (e.g. the correlation between $P(2)$ and $P(4)$) is given by ϱ and the process $X(s,t)$ is such that the correlation in time and space is given by the product of the correlation in space and the correlation in time we get

$$Cov(\bar{X}(s,i), \bar{X}(s,i-2)) =$$
$$\varrho\sqrt{V(i)\,V(i-2)}\int_Q\int_Q r(|s_1-s_2|)\,ds_1\,ds_2/|Q|^2,$$

where $r(|s_1-s_2|)$ denotes the correlation function in space (assumed to be isotropic) and $V(i)$ and $V(i-2)$ the variances of $\bar{X}(s,i)$ and $\bar{X}(s,i-2)$, respectively. This implies that the correlation between $\bar{X}(i)$ and $\bar{X}(j)$ is given by ϱ when $|i-j| = 2$. Assuming further that $\mathrm{Corr}(\bar{X}(i), \bar{X}(j)) = \varrho^{|i-j|/2}$ (essentially a Markovian assumption) and that $V(i) = \sigma^2$ for all i, the covariance matrix T of $\bar{X}$ becomes

$$T = \sigma^2 \begin{bmatrix} 1 & \varrho^{1/2} & \varrho & \varrho^{3/2} \\ \varrho^{1/2} & 1 & \varrho^{1/2} & \varrho \\ \varrho & \varrho^{1/2} & 1 & \varrho^{1/2} \\ \varrho^{3/2} & \varrho & \varrho^{1/2} & 1 \end{bmatrix}$$

For the moment the mean vector μ of $\bar{X}$ is assumed to be known. First we proceed as in the non-random case, i.e. calculate the estimators y_1, y_2, y_3 and y_4 and the covariance matrix Σ. Following Rao (1973, p. 234) the best linear unbiased estimator of $\bar{X}(4)$ (for example), is given by

$$z(4) = d+l_1y_1+l_2y_2+l_3y_3+l_4y_4,$$

$$\text{where } d = \mu(4)-\sum_{i=1}^{4} l_i\mu(i)$$

$$L_\star = \begin{bmatrix} l_1 \\ l_2 \\ l_3 \\ l_4 \end{bmatrix} = \Sigma^{-1}(T^{-1}+\Sigma^{-1})^{-1}\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

The (prediction) variance, $\tau^2 = \mathrm{E}[\mathrm{X}(4)-z(4)]^2$, is given by

$$\tau^2 = [0\ 0\ 0\ 1]\,(T^{-1}+\Sigma^{-1})^{-1}\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Summing up, in the random situation the best estimator $z(4)$ consists of a deterministic part and a linear combination of the best non-random estimators for the different periods. Thus, in the expression of $z(4)$, all the collected information is used, implying that the variance of $z(4)$ is always less than the variance of $y(4)$. The gain in precision is often rather large.

However, in practice the mean vector is not known. In this situation the estimators $z(4)$ and $y(4)$ agree. To overcome this problem we can, for example, assume that $\mu(t) = \alpha + \beta t$ and estimate α and β. In the estimation procedure we use y_1, y_2, y_3 and y_4 and information from previous periods if available. The estimated mean vector is denoted by $\hat{\mu}$ and the estimator of $\bar{X}(4)$ becomes

$$z_{\mathrm{mod}}(4) = \hat{\mu}(4) + \sum_{i=1}^{4} l_i\,(y_i - \hat{\mu}(i)).$$

Since we have estimated α and β, the variance of $z_{\mathrm{mod}}(4)$ is higher than the variance of $z(4)$ but, in most cases, less than the variance of $y(4)$.

Abstract

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The paper summarizes the methodical work preceding the introduction of the Sixth National Forest Survey of Sweden. Both theoretical and practical problems are considered. Thus the paper contains a discussion about permanent plots and describes the variables recorded, the data acquisition system, some results from field tests and the statistical considerations behind the new design.

Key words: National Forest Survey, sampling methods, permanent plots, temporary plots, data acquisition system.
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Preface

This report summarizes the methodical work preceding the introduction of the sixth National Forest Survey of Sweden. This work was organized in a research and development project named Nytax 83. The report quite closely follows the lay-out of that project.

The authors are responsible for different parts of the report as follows:

Thorbjörn Cruse: Data acquisition system, pp. 22 f.
Härje Jonasson: Field tests, p. 24.
Bo Ranneby: Statistical considerations, pp. 6–14; Discussion (part of), pp. 25 f.; Appendix, pp. 28 f.
Johan Swärd: Checking data, pp. 23 f.
Björn Hägglund: All other parts.

In short, Cruse, Jonasson and Swärd are mainly responsible for the practical questions in connection with the new survey, while Hägglund and Ranneby worked on the theoretical parts.

Acknowledgement is given to a large number of people who in different ways supported our work. Acting professor Göte Bengtsson, professors Nils-Erik Nilsson and Gustaf von Segebaden, now or earlier at the Department of Forest Survey, professor Bertil Matérn at the Department of Biometry and Forest Management, and professor Tryggve Troedsson and Dr Jan-Erik Lundmark at the Department of Forest Soils have given us many important ideas and also in some cases directly taken part in the investigations in their early stages.

Many questions were not fully clarified until the actual implementation of the research and development project in a working survey. Research leaders Bo Eriksson and Sven A. Svensson, systems specialists Lars Fällman and Tomas Johansson and a large number of field team leaders and crew members at the National Forest Survey played an important part in the final development of the survey.

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Umeå in June 1984

The authors

Background

The Swedish forests have been of great importance for the welfare of the Swedes for a long time. It was recognized at an early stage that knowledge of the forests— their area, volume, composition, etc. —is an essential pre-requisite for their utilization. This knowledge is obtained through forest inventories. For the whole of Sweden, National Forest Surveys (NFS) have been performed since the early 1920's. Over the years, the survey methods have been changed and adapted to new conditions several times. The latest change of methods occurred in 1983, when a new method was introduced in the so-called sixth survey. In this report, this new method and some of the work and considerations behind it are reported.

The NFS is a tool for decision-making on national and regional levels. The decisions made should aim at maximizing the long-term benefits from the forests. In national planning this might mean balancing resources put into and taken out of the forests. Historically, this process has passed through several stages. During the early period of forest utilization, the resources put in were strong men with axes and saws. There were forests enough for everybody, and it seemed quite meaningless to replant clearcut areas or to perform other types of silvicultural measures. However, as time passed it became evident that a high output from the forests in the long run requires a considerable input of silviculture. The concept of sustained—or even increased—yield forestry was born. This concept is now generally applied in forestry, at least in some parts of the world—northern Europe, for example.

This change in the attitude to forestry is also reflected in the methods of the National Forest Survey. Thus, the emphasis has slowly moved from estimating variables describing the state of the forest to the monitoring of changes and trends. Also the development of methods for long-term forecasting of timber yields has considerably affected the inventory designs in recent years (Fig. 1). The development process outlined is of course at different stages in different parts of the world.

The first NFS of Sweden was performed in 1923–

Level of forestry	Need of data	Type of inventory
Exploitation	State variables (volume, species, age, diameter, location)	State-oriented "one-shot-inventory"
	+	
Sustained basis. Extensive, cutting the natural growth	Growth, mortality, cut, simple growth prediction methods	Continuous inventory of simple type. Few variables
	+	
Sustained basis. Intensive management	Advanced models for long-term growth prediction, including effects of silviculture. Human influences on forest. Environmental changes	Change and trend-oriented, continuous, advanced, many variables. Combined with information from experiments.

Fig. 1. The relation between level of forestry, need of data for forestry planning and type of inventory method for producing data.

29. It was a strip survey at the county level, with a strip width of 10 m. In statistical terms it was a stratified systematic cluster sampling, a class of design which is still used.

It was soon realized that this design, due to the high correlation between adjacent points on forest land, was quite inefficient. The efficiency could be considerably increased by concentrating the measurements to sample plots along the survey lines. This was done in the second survey (1938–52), which was a line survey, using circular sample plots with radius 5 m. Like the first survey, it was performed county by county. This method costs less than a survey including all of Sweden every year, but on the other hand, data from different parts of the country are of different age. Because of this, together with a desire to obtain estimates of the annual cut for all of Sweden, the third (1953–62), fourth (1963–72) and fifth (1973–82) surveys covered all of Sweden each year. From the third survey, the design was changed through the introduction of "tracts"—square clusters of sample plots. On average, each cluster comprises one day's work for a field team (Fig. 2). This design has proved to be quite efficient and practical as long as the road network is not too sparse.

Concerning inventory techniques, the surveys have been based all along on field data only. It is not unlikely that the survey would have been more effective if good aerial photographs in a multi-phase design had been used. For practical and economic reasons (pp. 7f.), aerial photographs have not been introduced into the survey.

The Swedish NFS was computerized quite early. As early as 1965, prepunched cards were introduced for the recording of data in the field. An efficient system for data capture, check, transmission, processing, storage and retrieval has been built up over the years.

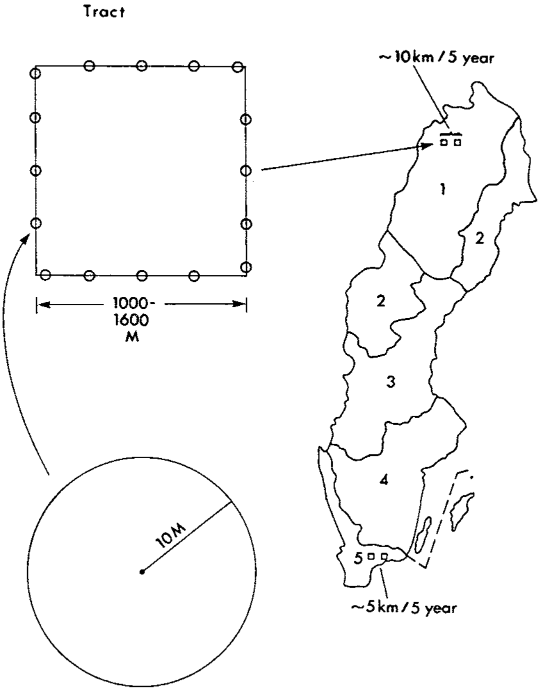

Fig. 2. The design of the 1973–82 National Forest Survey of Sweden.

Compared to the situation when the former surveys were designed, the following new factors have entered the picture and must be considered:

● As long as the cut was far below the sustained-yield level, changes in factors such as growth, cut and standing volume were not so critical. But when the cut, as is the case now, approaches the sustained yield, a new situation occurs. Changes in different variables must be estimated with higher precision and the survey turns more or less into monitoring.

● Forestry today is under discussion and there are many opinions about forestry methods, alternative ways of using the forest land, etc. Long-term forest planning must consider many different outputs from the forests, including recreation opportunities, protection, functions, etc.

● There is a great risk that pollution on a large scale will seriously affect the forests. Factors such as acidification, air-transported pollutants and increasing CO_2 levels might well be of decisive importance for the forests in the future. These factors must therefore be monitored as carefully as possible.

● Great progress has been made in statistics and computer techniques in recent years. Methods which were neither thought of nor feasible some years ago are now being considered for practical use.

In summary, these statements strongly indicated that the new survey, which started in 1983, should be based on a new statistical design and many new variables.

Aims and requirements

The process of formulating the aim of a NFS must start by identifying the users' need of information. Two inquiries addressed to the users were therefore compiled. One of these, Ilminge (1978), was directed to non-forestry users of survey data, for example authorities concerned with conservation, environmental protection and general land-use planning. The second inquiry, Hägglund (1979), concerned forestry authorities, companies and other organizations.

The area of information which survey data should —or at least could—elucidate is illustrated in Figure 3, which is inspired by Nilsson (1973). The functions of forest land can be divided into the production of measurable physical objects—trees, berries, game, etc.—and into functions which are not directly measurable, for example environmental protection and the beauty of the landscape. For each function of interest, state and change should be measured. Within these categories we might distinguish between potential and actual state and change, as well as variables faciliating analysis—so-called background variables (see Fig. 3). For example, for the forest function "wood production" we might be interested in the following variables:

	State	*Change*
Potential	site index	changes of basic site properties affecting site productivity
Actual	growth, standing volume, species, diameters, ...	change in growth rate, change in standing volume, ...
Background	age, species, standing volume, ...	silvicultural measures, weather conditions, pollution, ...

Note that the same variable might well fit into several places in the matrix in Figure 3.

Through the inquiries mentioned above, different users of survey data were confronted with the matrix in Figure 3. The traditional forest survey approach is to emphasize the function "wood production", aspect "state". Most users agreed that "change" in "wood production", was also of great interest. However, hardly anyone was willing to pay for better estimates of change by any decrease in precision (compared to the former survey) in important state variables. This indicates a rather delicate problem, as the resources for the survey would not be increased. Thus the effi-

	STATE			CHANGE		
Functions of the forest land	Potential production	Actual production	Background	Potential production	Actual production	Background
Measurable outputs · Wood (timber, pulpwood, fuel) · Berries · Game, fish · · ·						
Other functions · Environmental protection · Beauty of landscape · Conservation of plants and animals · · ·		Variables				

Fig. 3. The principal contents of a National Forest Survey

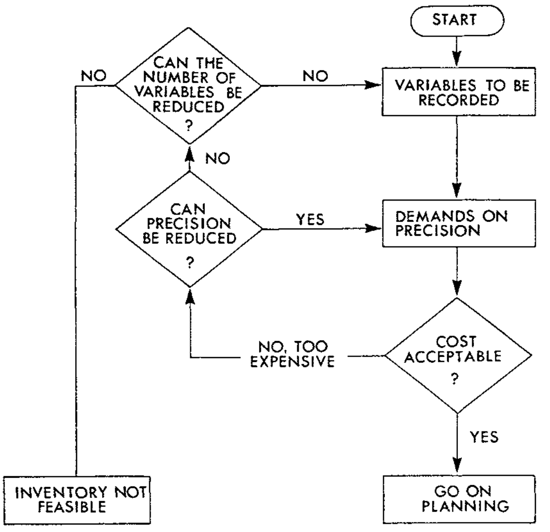

Fig. 4. Schematic flowchart of decision-making for the contents of a survey of a given design.

ciency of the survey had to be increased, for example through a new survey design. Considering forest functions other than timber production, there of course are specialists who normally emphasize their own fields. However, the general impression from the inquiries is that the interest in estimating variables characterizing functions of the forests other than "wood production" is not so great that substantial inventory resources could be invested.

One factor which receives a great and increasing interest in inventory is the large-scale pollution of forest land and its consequences for long-term soil productivity. It has been possible to raise special funds for these purposes.

Besides user inquiries, other sources of information have also been used for forming the survey. The international development of inventory has of course been important, as well as the ideas coming from the staff of the forest survey department. The general tendencies in thinking here are to give more emphasis to

- the estimation of changes, monitoring
- variables relating to factors other than timber production
- long-term aspects of forests and forestry
- the use of survey data for the construction of forecasting models.

Thus, from general thinking as related above, a set of variables to be measured was formulated, together with requirements as to precision for the most important variables. These wishes concerning the contents of the survey were then dealt with as is schematically illustrated in Figure 4. Of course, this decision-making is in reality intuitive to a large extent and must involve some conception of which design should be used and how the cost-precision relations are shaped for different variables.

The variable list obtained as the result of the process described is commented upon later, in the chapter "Variables recorded—some considerations" (pp. 17–21).

Statistical considerations

The need for models

In the literature on forest inventory, one can find much empirical evidence about the precision of various statistical methods in forest surveys. When comparing different empirical studies one finds that the conclusions about appropriate statistical methods can vary widely. This might be due to forests' being different but it may also depend on the fact that the estimated error variances are imprecise. This seems especially to affect the studies of systematic sampling.

In Matérn & Ranneby (1983) a situation is constructed, where a certain stratified sample and a systematic sample on the average will have the same precision. Imagine that we have data from 10 000 plots and form many samples, consisting of 400 plots each, from these 10 000 plots. When we compare the estimated error variances, it turns out that the relative efficiency of the systematic sample has a probability of 5% of being either lower than 61% or higher than 164%. Thus the practical conclusion from one empirical study can be imprecise, although the material consists of as many as 10 000 plots.

This fact points to the need for studying sampling and estimation procedures in mathematical model forests. By varying the fundamental properties of the model, one can find how the performance of different methods is affected by these fundamental properties.

Suitable models

Prior to the start of the sixth Swedish National Forest Survey, the possibility of achieving a higher inventory accuracy by using permanent sample plots, aerial photographs (or satellite pictures) or both was to be investigated. In Ranneby (1982), different models which can be used to compare the precision of different sample designs were constructed. As the "value" of permanent sample plots is to be investigated, models of the variation in both time and space are necessary.

The information obtained from aerial photographs is less exact than the information obtained from measurements on the ground. Using aerial photographs only allows a rough classification of the sample plots. For example, the sample plot can be classified as consisting (mainly) of water, land but not forest land, unstocked forest, young forest, thinning forest or final-felling forest. Models suitable for such descriptions are mosaic-models. We imagine that the plane is partitioned into convex cells which are "coloured" according to some probability law, giving a pattern of different colours – a mosaic.

As a first choice it seems reasonable to assume that the spatial process is locally stationary. Since our interest is concentrated on the variance of the errors occurring with different schemes of sampling and estimation, the only structural assumptions necessary concern the expected values and covariances attached to points (or plots) at different mutual distances and directions. If the direction is of minor importance, a further restriction is to assume that the spatial process is isotropic. (However, this restriction is not necessary; cf. the discussion of elliptic correlation.)

If the process is isotropic, the error variances will depend only upon a covariance function $c(v)$, showing the covariation of observations $Z(x_1)$ and $Z(x_2)$ of values attached to points (or plots) at the mutual distance $v = |x_1 - x_2|$.

In Ranneby (1982), some simple models having a spatial correlation which is isotropic are extended to models of variation in both space and time. For a large class of models, it turns out that the correlation function of the variation in space and time is given by the product of the correlation function of the variation in space and the correlation function of the variation in time. This property makes formulas for systematic sampling with partial replacement manageable.

Since, in practice, one often requires models in which neighbouring cells may be dependent, the models are constructed so that this requirement will be fulfilled. The variation in time can be given by quite different models. However, with the applications we have in mind it is highly realistic to assume that the variation in time is given by a non-stationary Markov process. The Markovian property means that if we have observed the values on a plot at times $t_1, t_2, \ldots, t_k$, where $t_1 < t_2 < \ldots < t_k$, the only value which will influence the future is the value observed at time t_k.

Possible sampling schemes

In the preparatory work on the new design we have to choose beteween and combine three different types of observations:

A. Ground observations on temporary plots
B. Ground observations on permanent plots
C. Aerial photographs or satellite images.

However, the schemes A, B and C can not be combined in an arbitrary manner since there are some restrictions. For example, increment cores have to be collected but we cannot bore on permanent plots. Thus temporary plots have to be included in all relevant sampling schemes. This implies that we have the following possibilities:

A
A + B
A + C
A + B + C

We made the following judgement: "Aerial photographs require a large staff of interpreters and today the quality of the satellite images is not satisfactory, but in a near future they will have almost the same quality as aerial photographs". Quite extensive studies indicated that the use of aerial photographs on our National Forest Survey scale is very expensive and impractical. One reason for this is that available photographs are on the average 3.5 years old. Consequently, in the present paper we will not treat sampling schemes where C takes part. Perhaps we overestimated the usefulness of satellite images – mainly because of the cost of obtaining these images. At the moment they are too expensive. Extensive studies are still to be conducted in order to clarify the future role of satellite images in forest survey.

The main idea is that aerial photographs or satellite pictures should be the first phase in a two-phase procedure. They could also be used for stratification. Even if the technique of remote sensing proves to be unusable, the possibility of a first phase remains. This is a consequence of the initiation, in Sweden, of a project called ÖSI in 1980. This is a stand-based inventory with many subjective elements, and the intention is that the inventory shall result in plans for all private forest owners. The results from this inventory might be more useful than aerial photographs. Although ÖSI will be an expensive inventory, the additional costs for using it in the NFS are small. (ÖSI will be performed regardless of how the NFS is designed.)

Systematic sampling and size and shape of the tracts

It was within forest surveying that sampling, or the random-sample methodology, first began to be applied. As early as 1830, Israel af Ström described a random-sampling survey of larger forests which could not be totally surveyed due to economic limitations. af Ström recommended a strip survey, which was the method used in the beginning. Quite soon it was recognized that almost the same precision could be achieved with a plot survey where the surveyed area was much smaller. Such results were, for example, reported by Gadd (1928). He obtained almost the same precision with a plot survey where the surveyed area was 1/40 of the area of the strips. The reason for this is that in the forest the variables are mostly positively correlated, so the extra information from a point which is close to another one is sparse.

The following discussions will be based on the assumption that the correlation is positive and monotonously decreasing with increasing distance between the sample plots.

In simple random sampling it may happen that some observations fall rather close to each other, implying that the precision is lower than that of a "sound" systematic sample. An even lower precision would be obtained if we gather the plots together (cluster-sampling).

For a large class of isotropic correlation functions, the best sample design is a systematic equilateral triangular lattice. However, a quadratic lattice performs almost equally well. An often reported drawback with systematic sampling is the difficulty of estimating the sampling errors. However, there are possibilities. A pioneer work in this field is Matérn (1947). He found that most formulas proposed for estimating the standard error of a systematic sample from the data of the survey itself were—for a rather general class of models—safe, in the sense that they gave no systematic underestimation of the error. In certain formulas the positive bias was moderate. The topic is further investigated in Matérn (1960).

Summing up, a systematic equilateral triangular lattice usually gives the highest possible precision among all sampling schemes with a given sampling intensity, and formulas can be constructed for estimating the standard error.

In practice, we also have to take the surveying costs into consideration and, when it is expensive to reach the plots, it might be meaningful to gather them into clusters. The size and shape of the cluster varies according to the circumstances. In the Swedish NFS the clusters are squares and the sample plots are located systematically along the perimeters of the squares. These squares are called tracts and the size of the tract corresponds to one day's work.

In the NFS the distance between tracts is large compared with the distance between sample plots in tracts. This implies that the covariances between tracts are approximately the same regardless of the shape and size of the tracts. Thus to rank different tract-designs it is sufficient to study the variance of the mean of the sample plot observations on one tract only. Using information from time studies of walking and working times, tracts corresponding to one day's work are constructed.

A good approximation of the correlation functions of variables studied in the forest, at least for distances larger than 100 metres, can be obtained by linear combinations of exponential correlation functions; see Matérn (1947, 1960), Ohlsson (1972) and Ranneby (1981*b*). At first we shall therefore consider exponential correlation functions.

We see from the table that when there is high correlation between the observations (low value of h in the table), the variance increases with increasing number of sample plots. This is quite unsatisfactory. To avoid this disadvantage we can use a weighted mean $Z_a = \Sigma a_i Z(x_i)$, where $\Sigma a_i = 1$. However, with high correlation the increase of information by new observations is small, and consequently the optimal

Table 1. *The variance of the mean of the plot observations of a tract with perimeter 4 kilometres and 4 m sample plots. Covariance function $C(v)$ = exp $(-hv)$. (The symbol v denotes distance and is measured in kilometres, while h is a parameter.)*

	h			
m	0.25	1	4	8
2	0.8293	0.5042	0.1727	0.1301
3	0.8326	0.5080	0.1558	0.0971
4	0.8338	0.5096	0.1502	0.0842

weighted mean will not be much better than the mean of equally weighted observations. Instead of using weighted means it is better to position the sample plots so that all of them contain real information.

The optimal distance between the sample plots depends on the variation in the region which is to be surveyed, and on which variable we are interested in. If we are interested in area-description variables, the distance between sample plots should be greater than if we are interested in the volume on the plot.

The results in Table 1 indicate that some care is necessary when the design of the tract is determined. To obtain good designs for the whole of Sweden, the country is divided into 5 regions with slightly varying designs for each. Furthermore, information is needed about the correlation functions for different variables and parts of Sweden. This will be discussed later (pp. 10f.).

In practice, it is not unusual to have different types of plots—one where only area-discription variables are recorded (area plots) and another in which measurements on the individual trees are aslo performed (volume plots). There are usually more area plots than volume plots. The extra area plots are situated between the combined area and volume plots. Owing to the high correlation for area description variables, the further information contained in these extra plots is very often almost negligible. Data from the Swedish NFS collected in 1973–77 showed that this was the case for us. The same standard errors were obtained with or without these extra plots. Another drawback with extra area plots is that the classification tends to be carried out by different methods on extra plots and combined plots, resulting in a risk of bias.

Studying the effect of different shapes of the tracts, we found that in Sweden a closed figure has many advantages and that a square is the most convenient closed figure if the correlation is isotropic (Anisotropic correlation functions are briefly discussed on pp. 11f.). From a practical point of view, probably the most interesting tracts are the "square", the "L" and the "line".

We compare first the "L" with the "line". Transportation from tract to tract is by car, so we have to return to the starting point. Taking this into consideration it follows that an "L" is preferable to a "line".

A comparison between the "L" and the "square" is more difficult since the "square" is closed but the "L" is not. A comparison, in which the different walking distances for the "L" and the "square" are considered, shows that high correlations between the observations are those which are favourable for the "L". However, the conditions in Sweden are such that correlations resulting in an "L" being better than a "square" appear very seldom. Further details can be found in Ranneby (1979*a*, *b*).

When the performance of different designs was studied, it appeared that the one-day-tract did not give a satisfactory result in southern Sweden. A one-day-tract system means clustering too many plots close to each other. Since the network of roads is dense in this part of Sweden, it was possible to use a system with tracts consisting of half a day's work. Such a system gives considerably higher precision for area-description variables.

The plot size

The effect of different plot sizes and the number of sample trees must of course be considered when the size and shape of the tracts is to be determined. All of the tracts we shall compare constitute one day's work. Thus if the plot size is increased, we have to decrease the side length, the number of plots on the tract or both.

The precision of estimates of area is mainly independent of the size of the sample plots, while the precision of estimates of stem volume/ha is plot-size dependent. The effect of this influence varies with the sampling design.

The optimum plot size depends on the variation between plots compared to the variation within plots. This is an approach used, for example, by Strand (1957). Here we shall use a slightly different approach, used in Ranneby (1981*a*).

The stem volume/ha on a plot can be viewed as a sum of two components, where one is obtained by a rough classification of the plot and the other gives the local deviation from the performed classification. For a circular plot with centre at the point s and radius r, the stem volume/ha $v(s,r)$ can be expressed as

$$v(s,r) = X(s) + e(s,r). \qquad (1)$$

In formula (1), $X(s)$ denotes the value obtained from the rough classification. All sample plots classified as belonging to a certain category have the same value for $X(s)$, while $e(s,r)$ denotes the local deviation from the "category-mean" $X(s)$. Since $e(s,r)$ measures the local deviation it is realistic to assume that $X(s)$ and $e(s,r)$ are uncorrelated. Furthermore, we assume that $e(s_1,r)$ and $e(s_2,r)$ are uncorrelated for rather short distances, while this need not be the case for the process $X(s)$. The variance of $e(s,r)$ depends on r, while the variance of $X(s)$ is independent of r. The variance of $v(s,r)$ is given by

$$\sigma_v^2(r) = \sigma_x^2+\sigma_e^2(r), \tag{2}$$

where σ_x^2 is the variance of $X(s)$ and $\sigma_e^2(r)$ the variance of $e(s,r)$.

To be able to compare different plot sizes we use the so-called "Fairfield Smith's law", (Smith, 1938), to get

$$\frac{\sigma_v^2(r_1)}{\sigma_v^2(r_2)} = \left(\frac{r_1^2}{r_2^2}\right)^{-b} = \frac{r_2^{2b}}{r_1^{2b}}.$$

The exponent b varies from area to area. In order to rank different tract designs it is sufficient to calculate the variance of the tract mean

$$\bar{V}_m(r) = \frac{1}{m}\sum_{i=1}^{m} v(s_i, r).$$

Here m denotes the number of sample plots per tract. If we assume that the process $X(s)$ is stationary and isotropic, we can write the variance of $\bar{V}_m(r)$ as

$$\mathrm{Var}\,(\bar{V}_m(r)) = \mathrm{Var}\,(\Sigma X(s_i)/m) + \frac{\sigma_e^2(r)}{m}. \tag{3}$$

To study the effect of different plot sizes, we have to know the correlation function of the process $X(s)$ and the ratio $\sigma_e^2(r)/\sigma_x^2$. Using data from the NFS collected during the period 1973–77, the required parameters are estimated. For this period, the plots had a radius of 10 metres, and it was noted whether the distance to the centre was less than 5 metres. Thus data from plots having radius 10 and 5 metres, respectively, were available. It turns out that for estimating stem volume in the NFS it is sufficient to use plots having a radius of 7 metres. This conclusion holds for temporary plots. Since the permanent plots are more expensive and are also to be used for yield research, they should be larger.

Estimation of correlation functions

Let $V(s)$ and $A(s)$ denote stem volume and percentage of forest land (of total land area), respectively, on a plot with centre s. The variation of stem volume depends on the variation of the per cent forest land and the variaion of stem volume/ha. We assume that

$$V(s) = \begin{cases} kA(s)+e(s) & \text{if } A(s) > 0 \\ 0 & \text{if } A(s) = 0 \end{cases}$$

where k is a constant, the expectation of $e(s)$ equals zero, and $A(s)$ and $e(s)$ are uncorrelated. The correlation function of stem volume/ha is estimated by estimating the correlation function of the process $\{e(s)\}$. The reason for this will be discussed below.

The covariance between $V(s)$ and $V(s+u)$ can be expressed as

$$Cov(V(s), V(s+u)) = E[Cov(V(s), V(s+u)\,|\,A(s), A(s+u))] + Cov[E(V(s)\,|\,A(s), A(s+u)), E(V(s+u)\,|\,A(s), A(s+u))].$$

Since

$$E[V(s)\,|\,A(s), A(s+u)] = \begin{cases} kA(s) & \text{if } A(s) > 0 \\ 0(= kA(s)) & \text{if } A(s) = 0 \end{cases}$$

and

$$Cov(V(s), V(s+u)\,|\,A(s), A(s+u)) = \begin{cases} Cov(e(s), e(s+u)) & \text{if } A(s), A(s+u) > 0 \\ 0 & \text{otherwise} \end{cases}$$

we get

$$Cov(V(s), V(s+u)) = P(A(s), A(s+u) > 0)\; Cov(e(s), e(s+u)) + k^2 Cov(A(s), A(s+u)). \tag{4}$$

By substituting $u = 0$ in (4) we obtain

$$\mathrm{Var}\,(V(s)) = P(A(s) > 0)\;\mathrm{Var}\,(e(s)) + k^2\,\mathrm{Var}\,(A(s)). \tag{5}$$

Suppose that the processes $\{V(s)\}$, $\{A(s)\}$ and $\{e(s)\}$ are stationary, with correlation functions $c_v(u)$, $c_A(u)$ and $c_e(u)$, respectively. Let

$$p = k^2\,\mathrm{Var}\,(A(s))/\mathrm{Var}\,(V(s))$$

and

$$g_A(u) = \frac{P(A(s) > 0, A(s+u) > 0)}{P(A(s) > 0)}.$$

With these notations we obtain from (4) and (5) that

$$c_v(u) = pc_A(u) + g_A(u)\,(1-p)c_e(u). \tag{6}$$

The correlation function $c_v(u)$ depends both on the correlation function of the percentage of forest land ($c_A(u)$) and the correlation function of the process $\{e(s)\}$, i.e. the correlation function of stem volume/ha.

It remains to give formulas for estimating the correlation function $c(u)$ of a stationary process, say $X(s)$. In time series analysis there are some different suggestions (see for example Fuller, 1976). In the French geostatical school (see Matheron, 1971), they estimate the variogram

$$v(u) = \frac{1}{2}(E(X(s) - E(X(s+u))^2 = c(o)(1-c(u)) = \sigma^2(1-c(u)).$$

We shall take the "French" approach and estimate both the variance σ^2 and the variogram $v(u)$. We use the following estimates:

$$\hat{\sigma}^2 = s^2 = \frac{1}{n-1}\left[\Sigma_{i=1}^{n} X^2(s_i) - (\Sigma_{i=1}^{n} X(s_i))^2/n\right] \quad (7)$$

$$\hat{v}(u) = \frac{1}{2n}\Sigma_{i=1}^{n}(X(s_i+u) - X(s_i))^2 \quad (8)$$

and

$$\hat{c}(u) = 1 - \hat{v}(u)/s^2. \quad (9)$$

If the process $X(s)$ is ergodic, which is a very mild restriction (for a definition, see, for example, Ibragimov & Linnik, 1969) then $\hat{v}(u)$ and s^2 converge with probability on to $v(u)$ and σ^2, respectively. This implies that $\hat{c}(u)$ converges to $c(u)$ with probability 1, i.e. for almost all realizations $\hat{c}(u)$ will be arbitrarily close to $c(u)$, provided that the sample size is large enough. Nevertheless, $\hat{c}(u)$ may deviate much from $c(u)$ for moderate sample sizes. To obtain useful estimates of correlation functions large data-sets are necessary.

To estimate the correlation function of the process $\{e(s)\}$ we apply formulas (7)–(9) with $e(s)$ defined by

$$e(s) = V(s) - \hat{k}A(s),$$

where

$$\hat{k} = \sum_i V(s_i)/\sum_i A(s_i).$$

Note that when we determine n in formulas (7) and (8), we must take into consideration that $A(s)$ and $A(s+u)$ shall be positive.

Several different correlation functions are presented (in diagrams) in Ranneby (1981*b*).

Location of tracts and elliptic correlation

In the foregoing we have described work which led us to a certain tract form. An efficient distribution of the tracts is also necessary. We still assume that the correlation function is isotropic. As mentioned on pp. 8 f. the best precision is obtained if the tracts are located in an equilateral triangular lattice, but a quadratic lattice performs almost equally well.

However, one often has reason to assume that the correlation is higher in some direction, and it is then necessary to modify the assumption about an isotropic correlation function. Starting with an isotropic process, we can easily define a process which is such that the correlation is highest in the y-direction, for example.

Let $Z_I(x,y)$ be an isotropic process with correlation function $r_I(\cdot)$. If we define the process $Z(x,y)$ as

$$Z(x,y) = Z_I(x,y/e),\ e>1, \quad (10)$$

the correlation will be highest in the y-direction. The process $Z(x,y)$ has an elliptic correlation function. Let B now be an arbitrary 2×2-matrix and $s = (s_1, s_2)$ an arbitrary point in R^2. The process $Z(s) = Z_I(Bs^T)$ yields the correlation function $c(s) = r_I(\sqrt{sB^TBs^T})$. Such processes are said to have an elliptic correlation function (see Matérn, 1960, p. 19). (The symbol T denotes transpose of vectors and matrices.)

If the process Z_I is stationary, the process $Z(x,y)$ defined by (10) also becomes stationary. Moreover, the process $Z(x,y)$ has the highest correlation in the y-direction, and for each given direction the correlation only depends on the distance between the points.

If we, with the sample intensity of 1 sample point/area unit, assign a regular lattice

$$R(\alpha) = \{(x_{ij}, y_{ij}) = (i\sqrt{\alpha}, j/\sqrt{\alpha}), i,j = 0, \pm1, \pm2, \ldots\} \quad (11)$$

the variance/sample point becomes (see Matérn, 1960, p. 81)

$$\sigma_E^2(R(\alpha),1) = \sum_{i=-\infty}^{\infty}\sum_{j=-\infty}^{\infty} c(i\sqrt{\alpha}, j/\sqrt{\alpha}) - \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} c(x,y)\,dx\,dy = \sum_{i=-\infty}^{\infty}\sum_{j=-\infty}^{\infty} r_I(\sqrt{\alpha i^2 + j^2/\alpha e^2}) - e\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} r_I(\sqrt{x^2+y^2})\,dx\,dy. \quad (12)$$

Assume now that the isotropic process $Z_I(x,y)$ has an exponential correlation function $r_I(v) = \exp(-hv)$. For a rectangular lattice with the ratio α between the lengths of the sides and a sample intensity of λ sample points/unit area, we denote the variance/sample point for the process $Z_I(x,y)$ by $\sigma_I^2(\alpha,\lambda)$. We obtain from (12) that

$$\sigma_E^2(R(\alpha),1) = \sigma_I^2(\alpha e, e). \tag{13}$$

Since $\sigma_I^2(k,e) = \sigma_I^2(1/k,e)$ we obtain from (13) that the lattices $R(1/ke)$ and $R(k/e)$ have the same precision.

Since a quadratic lattice is "almost optimal" for processes having an isotropic correlation function, it follows from (13) that the lattice $R(1/e)$ is "almost optimal" for the process $Z(x,y)$ defined by (10).

Table 2. *The variance/sample point, $\sigma_E^2(R(\alpha),1)$, for different values of α. Correlation function $c(x,y) = \exp(-h\sqrt{x^2+y^2/e^2})$*

		h		
e	α	1	2	4
2	1/2	0.160	0.311	0.556
2	1	0.201	0.379	0.630
4	1/4	0.114	0.224	0.422
4	1/2	0.144	0.278	0.500
4	1	0.277	0.513	0.798

Remark: When $e = 2$ the lattices $R(1)$ and $R(1/4)$ will have the same precision.

In situations in which we feel unsure about the value of e, we may use a quadratic lattice (an $R(1)$ lattice). From Table 2 we see that the difference between an $R(1)$-lattice and the "almost optimal" lattice $R(1/e)$ is large. If we assign a quadratic lattice with an angle of 45° to both the x- and y-axes the difference ought to be less. Define the lattice $S(1)$ as

$$S(1) = \left\{(x_{ij},y_{ij}) = \left(\frac{i+j}{\sqrt{2}}\right), \left(\frac{i-j}{\sqrt{2}}\right);\ i,j = 0, \pm1, \pm2, \ldots\right\}.$$

The variance/sample point becomes

$$\sigma_E^2(S(1),1) = \sum_{i=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} r_I \left(\sqrt{\left(\frac{i+j}{\sqrt{2}}\right)^2 + \left(\frac{i-j}{\sqrt{2}}\right)^2 / e^2}\right) - e\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} r_I(\sqrt{x^2+y^2})\,dx\,dy. \tag{14}$$

Table 3. *The variance/sample point of the lattice $S(1)$. Correlation function $c(x,y) = \exp(-h\sqrt{x^2+y^2/e^2})$*

	h		
e	1	2	4
2	0.158	0.307	0.553
2	0.143	0.278	0.500

The lattice $S(1)$ performs much better than the quadratic lattice $R(1)$, which was oriented as the axes. If $e = \sqrt{3}$ the lattice $S(1)$ is the optimal lattice.

As a consequence, if we have a rough idea that the correlation is higher in a certain direction, a robust design is obtained if a quadratic lattice is orientated so that it has an angle of 45° with the "correlation-direction".

Similary, a square tract can be orientated so that it has an angle of 45° with the "correlation-direction". However, in this situation the answer is not quite as obvious and the gain is moderate.

Temporary and permanent plots

In many situations it is possible to obtain better estimates if we are allowed to use both temporary and permanent plots. If the plots are distributed in a systematic way, we need models which describe the variation in both time and space in order to judge the magnitude of the sampling error. Such models have been described on p. 7.

The optimal proportion of permanent plots depends on which quantity we wish to estimate. If we are interested in the changes of the volume from occasion 1 to occasion 2, all plots should be permanent. Contrarily, if we want to estimate the mean of the volumes on occasion 1 and occasion 2, all plots should be temporary. If we wish to estimate current volume, it is optimal to use both temporary and permanent plots. The optimum percentage of permanent plots and the gain in precision (compared with temporary plots only) depend on the timecorrelation, which is closely related to the length of the rotation period. The gain is of importance only if the correlation is rather high.

When estimating the amount of fellings, the advantage of permanent plots is even more significant. In this situation the permanent plots give unbiased estimates with higher precision. It is doubtful whether it is possible to obtain unbiased estimates from temporary plots only. To obtain a really high efficiency, the time until the remeasurement of the permanent plots must not be too short (Matérn, 1980).

In the Swedish NFS we have decided to remeasure the permanent plots after 5 years. In the estimation procedure we can treat the population characteristics either as non-random or as random. In the first case we consider the collected data from 1983 and 1988 as a two-occasion sample. Best linear unbiased estimates then can be calculated in the usual way, see for example Jessen (1942), Patterson (1950) or Gurney & Daly (1965). We proceed similarly to obtain estimates for 1984 and 1989 and so on.

In the non-random approach, any relationships between successive values of the population characteristics are completely ignored. The effect of introducing such an association into the estimation process was first explored by Blight & Scott (1973).

However, if the population process is non-stationary with an unknown mean-vector, which is the most relevant assumption in our case, there are some problems. In Jones (1980), two approaches for overcoming this problem are reviewed. The first is to assume that stationarity can be achieved by differentiation, which is equivalent to assuming that we have a linear trend. A second approach is to assume a polynomial trend with constant coefficients, and then estimate this trend from the series of the unbiased estimators which can be obtained on each occasion.

Forestry literature mostly deals with the non-random approach (e.g. Ware & Cunia, 1962; Cunia & Chevrou, 1969; and Newton, et al., 1974), but there are also papers in which the random approach is discussed (Dixon & Howitt, 1979).

The differences between the two approaches are further discussed in an appendix.

Point- or plot sampling

A topic of discussion is whether the method with fixed radius (plot sampling) or the Bitterlich (relascope) point-sampling method should be used in forest surveys.

Several authors have compared the precision in point- and plot-sampling, among others Sukwong et al. (1971) and Matérn (1972). From Matérn (1972) we quote that, "to obtain the same precision for the two methods, the size of the sample plots must be chosen so that we get 50–60 per cent more calipered stems than the number of stems counted in the Bitterlich points". This statement holds for estimates of basal area/ha and probably also for estimates of standing volume of a compartment.

We raise the following question. Is it possible to use the Bitterlich angle-count method in connection with permanent plots, e.g. for estimation the change in basal area? In Ranneby (1980) it is shown that this is impossible owing to low precision obtained with point sampling. A slight extrapolation of the results in Ranneby (1980) shows that the point-sampling method is not usable without modifications if we wish to estimate anything other than basal area or standing volume. To obtain useful estimates it is necessary to measure the diameters of the selected stems. But then the great reduction in time consumption is lost, and many practical problems are encountered. This is especially the case if the points (plots) are permanent, e.g. the handling of ingrowth in permanent point sampling is quite complicated if the method is to be reasonably efficient (Kuusela, 1979). Another reason why we have preferred plot sampling is that the risk of introducing bias due to biased handling of border trees or hidden trees is, according to our experience, larger in point-sampling than in plot sampling. Of course, these problems could be successfully handled, as for example in the Finnish NFS, which is based on an extensive experience in point-sampling. In Sweden, the NFS has always been based on plot sampling, which is an important reason for choosing this method again.

The design

The new design will now be briefly described. The new NFS will consist of an equal number of temporary and permanent tracts. However, the size of the temporary and permanent tracts varies. To obtain efficient tracts over the whole of Sweden the country is partitioned into five regions (see Fig. 5).

In regions 1–4 the temporary tracts consist of 12 volume plots, each having a radius of 7.07 m. The side length of the tract varies from 1 800 m in region 1 to 1 200 m in region 4. The tract constitutes one day's work.

The permanent tract also constitutes one day's work in regions 1–4. The tract consists of 8 volume plots, each having a radius of 10 m. The side length of the tract varies from 1 200 m in region 1 to 800 m in region 4.

In region 5 the tract constitutes half a day's work. The plot radius is 7.07 m on temporary volume plots and 10 m on permanent volume plots. The side length is 300 m on the permanent tract and 400 m on the temporary tract. The numbers of plots are 4 and 8 on the permanent and temporary tracts, respectively.

To deal with a possible elliptic correlation, the pattern of tracts is arranged so that it has an angle of 45° with the supposed "correlation-direction".

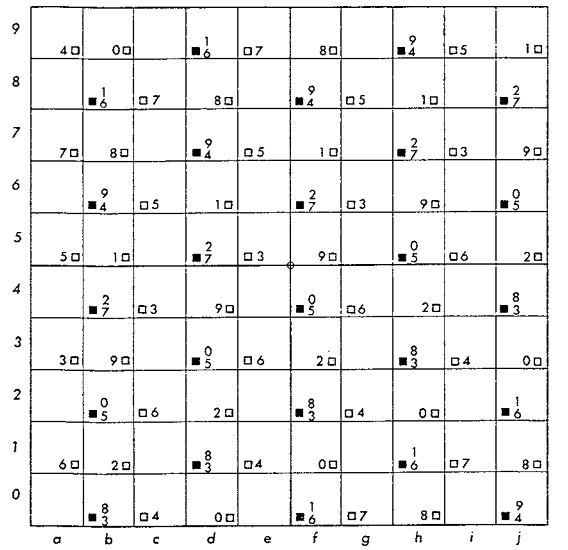

Fig. 7. Example of distribution of tracts during the peiod 1983–92.

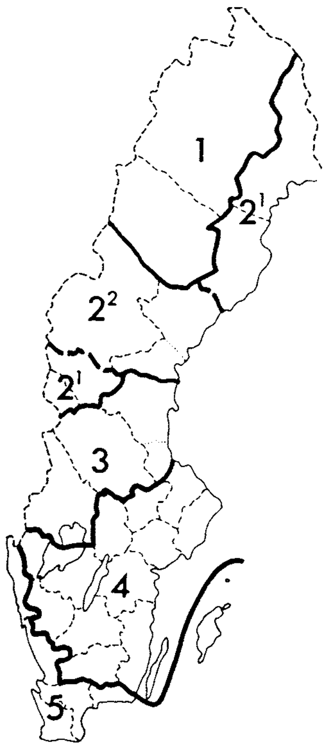

Fig. 5. Division into survey regions in the new survey.

The tracts are situated so that the temporary and permanent tracts follow a regular pattern both when they are treated separately and in combination (see Fig. 7).

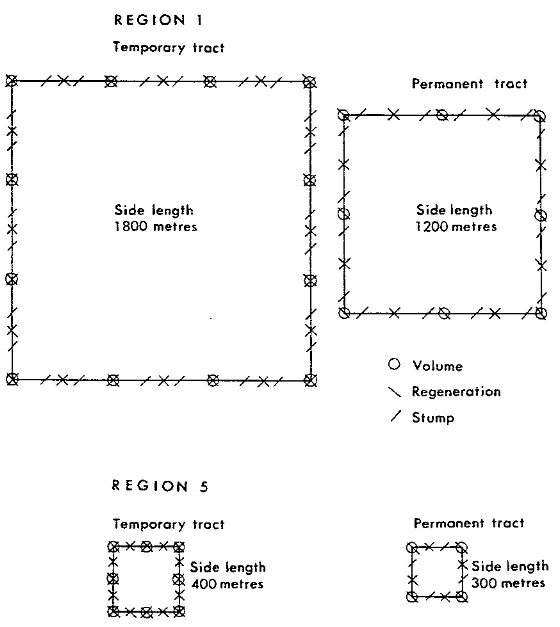

Fig. 6. Example of tracts in the new survey.

Permanent plots—why and how?

In the foregoing, the statistical basis for using permanent plots in the survey was given. To conclude: As the estimation of changes is emphasized among the goals of the survey and permanent plots are very efficient for this purpose, such plots should be used in the survey.

However, permanent plots also have distinct advantages from other points of view. For example, they will provide data very useful for the analysis of consequences of different silvicultural measures. When a permanent plot has been measured a number of times, the data will comprise quite long time-series together with well-known stand history. These time-series form a true sample from the forests. Thus, these data could be very effectively used for the construction of growth functions and other aids for forecasting the effects of different forest management regimes.

The permanent plots should be concealed from everybody except the survey team which does the remeasurement. If this is not the case, the permanent plots might be treated in a non-representative way, leading to biased survey results. One reason for having a considerable portion of temporary plots in the survey is to check for large deviations of this type.

It is not always easy to combine the concept of hidden plots with the team-leaders' wish for plots which are quickly and easily found at the time of remeasurement. Since 1971, we have made experiments with different methods of marking permanent plots (von Segebaden, 1977; Swärd, 1980). This study is briefly reported below.

In 1971, 344 sample plots clustered in 23 tracts were laid out. The plots were marked in the field by various methods. They were remeasured in 1972, 1974, 1976 and 1979. In total, about 2% of the plots were not found at the last remeasurement, 8 years after the establishment. We think this loss of plots is reasonably low, especially since most of the lost plots were situated on areas which were clear-felled during the observation period. On such places where extensive forestry operations have been performed, the plots could be re-established a few metres from the original centres without any major disadvantages.

The following practical experiences were gained from the study (Fig. 8). At the start of a day's work, an aluminium pole, about 1.5 metres long, should be placed out, marking the point where line measurements begin. At least two well-defined objects in the terrain should be identified and their polar coordinates in relation to the startingpoint recorded. Every 100 m of the tract side, a small plastic tube should be placed and paint sprayed on stones or stumps close to the line. The centre of each plot is marked with a small aluminium stick and the polar coordinates to some well-defined objects are given. No colour marking is done on the plots. An important aid in finding the exact centre of the plot at the time of remeasurement is a map, showing the positions of the trees on the plot. Data for this map are obtained through the recording of the polar coordinates of all trees greater than 10 cm DBH, as well as all sample trees and, in young stands, all main stems to be left after precommercial thinning. This idea with plot-maps based on polar coordinates was originally developed in Switzerland (Schmid-Haas, Werner & Baumann, 1978) and has been used extensively there with good results. It seems as if the position of the trees on a 10-metre circular plot is as unique as a finger-print.

One special problem connected with the use of permanent plots is the accuracy of repeated measurements. This question has been studied in different ways. The accuracy of diameter measurements was investigated in a study in which 20 persons each measured the same 200 trees with three different methods. The first method (A) was to caliper the trees at breast height, using a 1.3 m stick for determining height. In the second method (B), a mark on

Table 4. *Markers placed out and found (from Swärd (1980))*

Marker	Number of markers placed out	Percentage of markers remaining on different occasions: after 1 year	after 3 years	after 5 years	after 8 years	average loss/year
Iron rod	337	99.2	95.5	91.4	83.4	2.1
Plastic tube	337	97.3	94.0	89.9	83.1	2.1
Plastic stick (white)	673	91.1	79.5	67.5	41.4	7.3
Plastic stick (yellow)	673	90.0	76.8	61.1	31.2	8.6

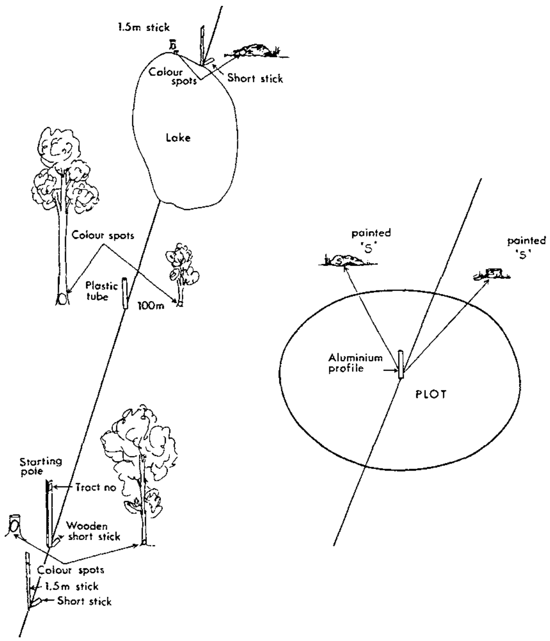

Fig. 8. Marking permanent tracts and plots.

the clothes about 1.3 m above the ground was used, while no aids at all were permitted in the third method (C). The direction of the caliper was fixed and the same for all methods. In total, almost 4 000 diameter measurements were made. The design was rather balanced, different persons starting with different methods on different plots, etc. The results are given in Table 5.

F1 and F2 are two Finnish Studies, Kujala (1979) (F1) and Päivinen & Yli-Kojola (1983) (F2). The results seem quite consistent with our study. The standard deviation between operators increases as expected from A to C. We find it difficult to explain why the method which should be most accurate (A) gives the highest total variation. However, one has to remember that the estimated standard deviations are just estimates and then due to sampling errors.

Turning to the measurement of heights, Eriksson (1970) estimated the standard deviation of height measurements made with the Suunto hypsometer to be about 0.5 m. In the Finnish studies mentioned above, the corresponding deviation was estimated to be 0.5–0.8 m, while the standard deviation between operators was 0.2 m. As the Finnish and Swedish results agree very well, the Finnish figures on the precision of measurement of single tree volumes should be approximately valid also for Swedish conditions (Päivinen & Yli-Kojola, 1983). These figures are quoted below.

The measurement error of single-tree growth, estimated as the difference between two volumes, will of course be quite large. For example, if the growth rate is 3% and the measurement errors are independent between measurement occasions, then the measurement error of 5 years' growth will be about 45% for a 20 cm tree.

These quite large errors will decrease very much when data from a number of plots, instead of from one single tree, are considered. The measurement error for a single plot is difficult to calculate precisely here. The problem is that the measurement errors of single trees must be considered to be dependent at plot level. Further, the single tree measurement errors are calculated as if the height is measured. This is often not the case. Instead, the heights are derived from a height curve. Matérn (1980) assumes that the measurement error at plot level is 3% of standing volume, a figure which seems quite consistent with the results of the Finnish studies. Assume now that the measurement error and the relative annual

Table 6. *The precision of measurements of single tree volumes. Figures from Päivinen & Yli-Kojola (1983) obtained by simulation*

DBH, cm	Measurement error, standard deviation, % of volume
10	10
20	5
30	4

Table 5. *The accuracy of diameter measurements*

Method	Deviation (D) from true value, mm	Standard deviation of D:s mm	Standard deviation between operators, mm
A	0 (by definition)	5.1	0.6
B	0.3	4.7	1.1
C	−0.4	4.4	1.3
F1	0.1	4.0	0.9
F2	-0.4	4.9	1.8

growth are of the same size. Then we obtain, regardless of the numerical value of the measurement error, the following formula for the standard error of the estimated mean annual growth of a stratum, as estimated from permanent plot data:

$$e_i = 100 \cdot \frac{\sqrt{c_i^2 + 2 \cdot 1^2/k^2}}{n_i}$$ per cent of mean annual growth, I_m,

where e_i = standard error of mean annual growth estimate in stratum no. i

c_i = the standard deviation of true growth between plots in stratum i (% of I_m)/100

k = the growth period, i.e. the time between two measurements of the plot

n_i = number of plots in stratum i.

If we assume c_i to be 0.7, and k to be 5 years we obtain

$$e_i = 75/\sqrt{n_i}\ \%\ \text{of}\ I_m.$$

For 100 plots we obtain a standard error of estimated growth of about 7.5%, for 1 000 plots about 2.5%.

As Matérn points out, small values of k (1 or 2 years) will give quite large relative standard errors. Probably, shorter periods than 5 years between measurements should normally not be used.

To conclude, we consider that the measurement errors should not seriously hamper the use of permanent plots in forest survey. However, it seems wise to make the measurements quite carefully and, for example, to use a 1.3 metre stick for the measurement of DBH.

Further discussions on and experiences with the use of permanent plots in forest survey can be found in Nyyssönen (1967).

Variables recorded—some considerations

General

A list of the variables recorded in a survey reflects the aims in a very straightforward, explicit and precise way. Often the aim of the survey is actually clearer from a list of variables than from some vague, overall formulation of aims.

In an earlier chapter, the aims and requirements of the survey were reported together with the sources of information used for formulating the aims. These sources also were used for deciding which variables should be included in the new survey. However, we did not start from scratch here. As the NFS of Sweden is continuous, the continuity between the former and new surveys is important. Therefore, the old NFS is a most important basis for choosing variables for the new one. We did not change variables without good reasons.

Three general remarks concerning the formulation of our variable list follow:

- Data collected and data used for displaying forest conditions are not necessarily the same. For example, volume is very seldom measured directly. Instead, diameter, height and possibly some further variables are measured and transformed to volume by means of regression functions. One specified "result variable" also might give several choices of variables to be recorded.
- As far as we can see, there does not exist any practical way of objectively deducing the "optimal mix" of variables for a given survey. As for many other parts of survey design, common sense and some intuition in identifying the relevant problems of the future are needed.
- The cost of recording one more variable might be calculated in different ways. The result will be much more favourable for the variable considered if the marginal and not the mean cost is used. We consider the marginal cost to be the correct figure to use. Thus, there are rather many variables in our survey.

The character of the present survey is multipurpose monitoring of nonurban and non-agricultural lands, strongly emphazising data relevant to forestry. The survey is divided into two parts, mainly due to different parent organisations and ways of financing. The major part is a forest survey which mainly elucidates conditions important to forestry. However, a special site survey is also performed on the permanent plots, aiming at environmental monitoring. This of course includes, even emphazises, variables important to the long-term productivity of forest soils. This site survey should not be confused with the simple "site block" of the forest survey (See below). The variables recorded are structured into five major blocks, namely:

- Site
- Area variables
- Volume, growth and mortality
- Regeneration
- Cut.

The contents of each block are briefly discussed below.

Site

The site block is dominated by those variables needed for estimating site index according to Hägglund & Lundmark (1977). This means estimating site index (dominant height at a total age of 100 years) by means of dominant height and age in pure even-aged, undamaged conifer stands. Site variables are used in all other cases. These site variables include altitude, latitude, ground vegetation type, soil hydrology, soil depth and texture, and local climate type defined as maritime, intermediate or continental. Some of these variables are also useful for other purposes, such as judging the difficulty of regeneration work.

The properties of forest land often vary over short distances, even within a sample plot with 10 m radius. A site index estimated from dominant height and age is not always representative for the whole plot, for example. The biggest trees might be situated on the best part of the plot and the index thus be biased upwards. In order to obtain some idea of the magnitude of this problem, some hundred survey plots of 10 m radius were investigated for improductive spots within plots classified as productive land. However, the area of these spots -small rocks, swamp patches, etc. —was only about 1% of the total area and thus too small to be considered in the new survey. There was a systematic variation in the improductive spot area such that it increased with decreasing site index.

Game, especially elk (moose), has in recent years caused great damage in conifer plantations. Therefore, the occurrence of damage and factors affecting damage are also of great interest in the survey. The amount of damage is recorded in the area block, while the amount of game food and the degree of browsing are parts of the site block. The estimation is made ocularly, approximately in accordance with the method presented by Ahlén (1973), which has also been used in earlier surveys. The main idea is to judge the relative occurrence (coverage of plot area) of certain species of trees and bushes and the degree to which these are browsed.

Area

By "area variables" we mean variables used for subdivision of data on an areal basis. Generally, the different variables describe the stand or compartment in some way—they are either stand variables (density class, age class, basal area per ha, etc.) or variables expressing, for example, the accessibility of the stand (terrain class, distance to road, etc.). By definition, the area variables are always linked to a specified unit area. This unit can be:

- The compartment in which the plot is situated
- A circular plot with radius 20 m, area 0.12 ha
- A circular plot with radius 10 m, area 0.03 ha.

Generally, it is desirable to have as many area variables as possible reflecting compartment characteristics. The reason for this is that the compartment is the operable unit in forestry. Let us take an example. We consider the variable "estimated (by relascope) basal area per ha" and the distribution of forest land area by basal area classes.

The smaller the area to which the basal area applies, the wider will the distribution of area be. If the area of, say, very dense forests is estimated from plot data, this estimate will evidently not be applicable to compartments without correction. As practical forestry operations by definition cannot be performed for units smaller than compartments, the practical consequences of the problem described might be considerable. Even if there exist methods for correction of the deviations (Hägglund, 1982), it is preferable to estimate compartment data directly. However, there are of course some practical problems in estimating compartment data in forest survey. It is difficult,

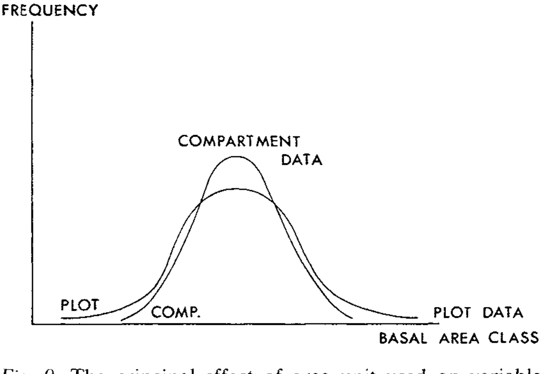

Fig. 9. The principal effect of area unit used on variable distributions. Example.

often impossible, to gain an overall view of the stand without spending too much time. In the new survey, we have dealt with the "plot-compartment-problem" in the following way:

- The definition of compartment in the field manual is quite strict.
- The field crews use aerial photographs (stereo pairs, 1:30 000, black and white) for the delineation of compartments.
- A few variables, such as the cutting class and operations performed and proposed (see below), apply directly to the compartment.
- For some important variables, which are primarily estimated on a plot basis, the deviations between plot and compartment conditions are estimated in a few, broad classes.

Many of the area variables are merely ocular judgements, rather than objective measurements. These variables are often basically very complex. Two important examples of this type of variable are the cutting class and the degree of site utilization. These might be combined as shown in Figure 10.

Cutting class		Site utilization			
		Good (1)	Satisfying (2)	Not fully satisfying (3)	Poor (3)
Bare land	(A1-A2)				
Young stands (three sub-classes)	(B1-B3)				
Medium-aged stands (three sub-classes)	(C1-C3)				
Old stands	(D)				

Fig. 10. Cutting class and degree of site utilization in combination.

There is a large number of rules more precisely defining the different classes. Why is then this type of variable included in the survey? Would it not be possible to obtain the same information in a better way by combining objectively measured variables? One reason for using "judgement variables" is that some of them apply to compartments and no correct measurements are obtainable for this unit. Further, for example, the cutting class variable comprises elements which are difficult to measure objectively, such as the vitality and quality of the stand. Thirdly, the cutting class and other "judgement variables" are among the most frequently used in result presentation. The demand for these variables is very great, probably because they tell us important things about the forest in a simple, though somewhat subjective, way.

Describing the impact of man on the forest is a very important part of the survey. We try to record the operations performed in the compartment in which the plot is situated as well as possible. These data indicate the need of introducing new forest policy means. They also express the effect of the present forest policy. Especially on permanent plots, data on operations performed can be linked to effects in terms of growth and mortality, for example. These operation-effect data can be used for the construction of models for long-term forecasting.

Within the set of area variables are also proposals concerning which operations should be performed in the compartment within the next 5 and 10 years. These proposals are made in accordance with official forest policies and will express what areas and volumes of forest are available for or in need of different operations as a result of the present forest legislation or silvicultural standards. Of course, these data have great relevance for the formulation of forest policies.

Not all operations performed in the forest are easy to detect. We have considered several methods for detecting fertilization, as this is an important operation in Swedish forestry with a strong influence on growth and ground vegetation. For example, we tried to trace chemical differences in the wood formed during the five years following fertilization compared to the wood in unfertilized stands. No significant differences were detected. The only possibility we can see at the moment is simply to ask the forest owners whether, when and where they have fertilized. This method has been successfully tried (Bengtsson & Sandewall, 1978) and will be feasible as long as only large companies and the Forest Service fertilize. But when the 240 000 private forest owners in Sweden start fertilizing, the inquiry method will be impossible to use.

5.4 Volume, growth and mortality

Volume, growth and mortality are estimated from fixed-radius plots. Permanent plots have a radius of 10 m, temporary plots 7.07 m.

On the survey plots, all trees larger than 10 cm DBH are calipered. The smaller trees are measured for DBH on a part of each plot. Sample trees are taken randomly with a probability increasing with the diameter of the tree. See an example in Figure 11. In total, about 23 000 sample trees are taken on forest land each year. This means, on the average, about 2 sample trees on each permanent plot and 1 on each temporary plot. The number of sample trees taken here is probably too high if only volume and growth estimation are considered (Matérn, 1981). It would have been better to take fewer sample trees and to allocate the resources available to sampling more plots instead. However, the relatively large number of sample trees is justified by the use of data for the construction of growth functions, annual ring indices, etc.

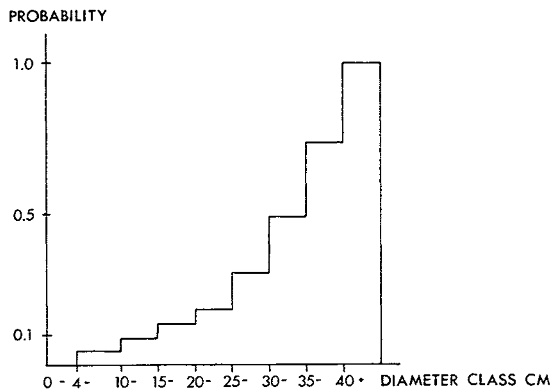

Fig. 11. The probability of a tree's being chosen as a sample tree. Example.

Sample trees are measured for those variables needed for the estimation of single tree volume. Methods for this purpose were investigated by Swärd (1981). Several volume functions (volume as a function of diameter, height and other variables) were compared. For Swedish conditions the following conclusions were drawn:

- For the estimation of total standing volume for reasonably large strata, the volume functions could be quite imprecise and simple as long as they are not biased for the stratum in question. The number of plots and trees measured is more important than the volume function.
- With simple volume functions, there is an evident risk of bias for small strata, or extreme strata or both, such as coastal areas, areas at high altitudes or recently thinned stands. This risk of bias is considerably reduced if more precise volume functions are used, as for example functions including an upper diameter as an independent variable (Pollanschütz, 1965). Therefore, an upper diameter is measured on sample trees on permanent plots in the new NFS.

Besides variables used for single tree volume estimation, some other variables, such as the amount of cones, the tree class and possible defects of the sample tree, are also recorded. Additionally, on temporary plots, bark thickness is measured and a core is taken for the estimation of age and growth. Due to the risk of influencing future diameter growth, cores are not taken on permanent plots (Vuokila, 1976).

Figure 12 shows how sample tree data are used for the calculation of forest volume and growth. The figure applies to temporary plots. On permanent plots, growth (mortality and cut, see below) are estimated by calculating differences between standing volumes on two occasions.

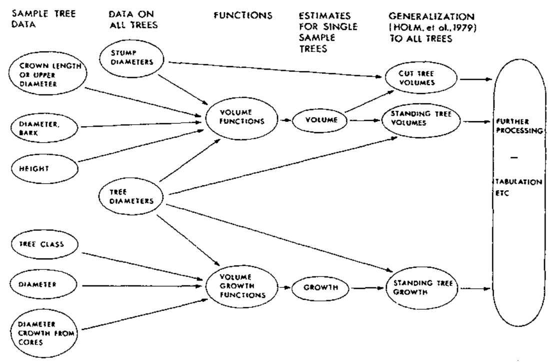

Fig. 12. Schematic illustration of the estimation of standing volume, growth and cut on *temporary* plots.

In the former Swedish NFS, mortality was estimated through recording each dead tree which is not completely rotten and judging the time of its death. This judgement is of course difficult, and so is the estimation of annual mortality. The introduction of permanent plots will make the estimation of mortality easier and (probably) more accurate.

Regeneration survey

The quality of the regeneration work is very important for the future development of the forests. In Sweden, large sums of money each year are invested in the regeneration work. It is important to monitor the outcome of these investments by means of solid data from regeneration surveys. On a national level, such data tell a lot about the effects of forest policy legislation, the need for new actions and the sustained-yield level.

The regeneration survey is performed by means of special plots, placed along the sides of the tracts. The distance between the regeneration plots is on average about half the distance between the volume plots. Regeneration plots are inventoried while the mean height of the stand is below 1.3 metres. The measurement program includes:

- A special-area variables inventory, describing the stand and the operations performed together with many of those variables included in the ordinary area inventory
- A plant inventory.

At the plant inventory the total number of plants as well as the number of main plants are estimated. A main plant is a plant being left after a "theoretical" pre-commercial thinning. Further, the size, species and spatial distribution of the main plants are recorded. The inventory is performed by systematic sub-sampling within a circular plot with radius 20 m. The sub-sample is comprised of 5 circular plots, each with the radius 1.78 m^2. This means that the regeneration survey now applies to a larger plot (1 257 m^2) than earlier surveys (1973–82: 96 m^2, 1964–72: 15 m^2). Even if the new survey means lower precision in the estimation of plot averages, the short-distance spatial variation is quite high in regeneration areas, and thus an increased plot size would considerably increase the total precision of the survey. The loss of precision in plot averages will therefore be more than compensated for.

Annual-cut survey

Also in the new survey, stumps from trees felled during the last felling season are measured in order to estimate the annual cut. The annual-cut survey is performed on temporary plots with the radius 7.07 m placed along the sides of permanent and temporary tracts. These plots are never placed so that they coincide with permanent plots. This is because the search for stumps involves the removal of logging residues, a measure which could disturb the future development of the stands on the permanent plots.

The annual-cut inventory as described above was introduced by Hagberg (1952). It has been a part of the Swedish NFS since 1952. Check surveys and comparisons with other data on annual cut show that the stump measurement method underestimates the true cut by about 5%. The main reason for this is that it is often difficult to find the stumps under large amounts of logging residues. Also the judgement of the time of the cut—if the cut has been carried out within the last felling season or not—is difficult, and might cause bias. However, until now stump inventory has been the only method yielding data usable for qualified analysis of the cutting patterns in Sweden. The outcome of this inventory has also greatly influenced Swedish forest policy, especially during the last 10–15 years.

By the introduction of permanent plots, unbiased estimates of cut can be obtained. These estimates will be combined with the estimates obtained through stump measurements. Permanent plots will primarily yield results as sums for five years only. However, permanent plots also yield information about the stand and the trees before cutting, and this will make it possible to make new and very important analyses in future.

Site survey

Forests and forest soils today are influenced, perhaps threatened, by air-transported pollutants such as sulphur and nitrogen acids and oxides, ozone and heavy metals. Further, forestry itself might in some cases influence the long-term productivity of the soils. In this situation it is very important to monitor carefully changes and trends in variables relating to the health of the forests and to the productivity of the soils. The Department of Forest Soils at the Faculty of Forestry has therefore started a detailed site survey on the permanent NFS plots. This new site survey is a methodological development of earlier surveys of this type, performed in connection with former NFS (Troedsson, 1966).

The site survey comprises measurements such as the following:

- Ground vegetation in some detail
- Different humus layers
- Soil characters such as soil depth, texture, and hydrology.

Further, the humus layer and the mineral soil are sub-sampled. The samples are transported to the laboratory for analysis of nitrogen, pH and probably also heavy metals.

When the network of permanent plots is fully established, the site survey will yield data from about 20 000 permanent plots on forest land. These data could easily be combined and co-analysed with NFS data on forest growth, forest operations performed, etc. All in all, we believe that the combination of a detailed site survey and a NFS with permanent plots yields an excellent data base for the integrated monitoring of forest resources and environmental status.

Field work

The Swedish NFS—new and old—is almost entirely based on field work. High efficiency in field work methods is therefore very important. Some elements in the rationalization of field work are reported below.

Staff

The size of the NFS team has successively decreased from about 10 persons in the 1920s to 5 persons in the 1973–82 survey and 3 persons (plus one site specialist) in the new survey. At the same time the number of variables and the amount of data have increased. The major reasons for this remarkable rationalization follow below:

- The increased possibilities of fast transportation (each team now has a car and the road network is dense) has radically increased the proportion of time used for real inventory work compared to transportation. If we consider a long time-span, this might well be the most important factor.
- Over the years, variables which demand much time for measuring and still do not give much information in return have been removed from the survey.
- Methodological details, instruments, etc. have successively been refined.
- The training of the staff has increased all the time and is now intensive. It has become evident that investments in education soon pay off.
- The introduction of computers has successively created more effective methods for recording and checking of data. Recently, hand-held micro-computers have been introduced as tools for data recording and checking (see below).

The new NFS is performed by 22 ordinary field teams and 2 check teams (see below). Each team has 4 members, one of whom is a site survey specialist in charge of the special site inventory.

Data acquisition system

The amount of data recorded during one year's NFS is considerable. In total, the field teams measure about 200 different variables on about 18 000 plots. These data must be recorded, transmitted, checked and stored in an efficient way.

Beginning in 1967, the Swedish National Forest Survey used pre-punched cards for the recording of data.

From 1978 there was no production of pre-punched cards in Sweden. This and other reasons made it difficult to use this system in the new NFS. Two other techniques for recording data therefore were studied in 1979—namely, optical character recognition (OCR) and an electronic data collection system (Jonsson, 1981).

Very stringent demands must be made concerning the performance of data collection equipment under difficult conditions (rain, cold, shocks) in the field.

OCR means that data are recorded with figures on a special form which is read by an electronic machine. The figures must be plain and the forms clean. If not, there is a great risk that the machine will misinterpret a figure or not be able to read it at all. For the Swedish NFS it was necessary to use nine different forms.

The other system tested was a hand-held micro-computer attached to a caliper for automatic recording. The test was performed by a crew consisting of three persons. Before the study the crew was trained for three days on each recording method. The test area consisted of six tracts.

The main result of the study was that the difference in the total time between the two methods was very small. Another conclusion was that it was a great disadvantage to have nine different forms in the OCR-method. They occupied much space and it was difficult to prevent them from becoming dirty or damaged.

As the team only had one micro-computer, it was necessary to use forms to record data when the terminal was occupied. Afterwards, data had to be transferred to the terminal and during this transfer many mistakes were made. Moreover, the connected caliper did not work properly all the time.

Despite these problems, the study showed that the tested systems were both rather good. The knowledge that problems of the micro-computer could be solved in the near future, and the rapid development in the computer field, were good reasons for choosing this system.

During the following field season, different types of micro-computers were compared. It became evident that the most suitable computer for our purpose was the Micronic 445, used without any directly connected caliper.

Micronic 445 is intended mainly for use indoors. Many improvements were made to make it useful outdoors as well. Moisture and mechanical shock were the biggest problems faced. A new aluminium casing solved both problems.

Two micro-computers are used by each team, with identical programs, which means that it is possible for the teams to carry out the inventory with only one micro-computer working.

One important advantage when using micro-computers is the possibility of checking the data in the field. Every piece of data which is entered on the keyboard is checked to see if it is within allowed limits. It is also, in some cases, checked against other variables. If the datum is not accepted, it is impossible to enter it until it has been corrected.

Data entry in the micro-computer is organized as "menus", one for each information block. The menus can be chosen almost independently, and each menu contains a sequence of questions and value checks for different variables. Every variable is prompted and the next will not appear until the previous one has been answered.

Every second day the collected data are transmitted to a large central computer, a CYBER 170–730, where more complicated tests are carried out. The results of these tests are sent, by post, to the team. After correction, data are stored on discs for further processing.

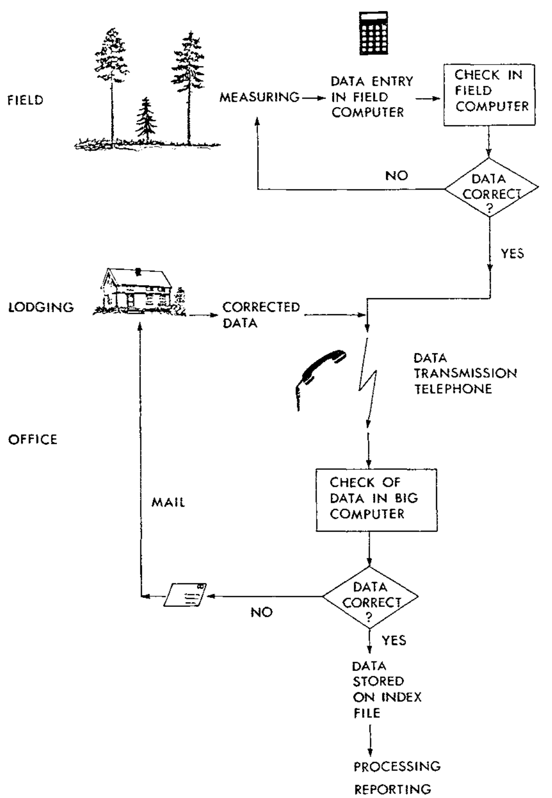

Fig. 13. The data recording system of the Swedish NFS.

The transmission is done on the telephone net, and the transmission speed is 300 bps. To be sure that the data recieved by the central computer is the same as the transmitted data, a protocol is used. When each data block is transmitted, a check sum is completed. The Cyber also computes the value of the check sum, and if this check sum is the same as that recieved, the block is accepted. If not, the block is retransmitted.

If, for any reason, it is impossible to transmit the collected data to the Cyber, it is possible to use a "mempack" to store the data. The mempack consists of a solid-state memory of the same type as in the micro-computer. The mempack can hold data from two micro-computers, and dumping the data from the micro-computer to the mempack takes about 3 min.

Technical specifications

MICRONIC 445
CPU: COSMAC RCA 1802, 8-bit processor
RAM: 24 kbyte (48 000 digits) CMOS
ROM: 16 kbyte (32 000 digits)
Display: 16 digits, LCD
Total current consumption: 5mA
Operating time: ~ 100 h
Program size: 28 kbyte (16 kbyte ROM, 12 kbyte RAM)

MEMPACK
RAM: CMOS, 24 kbyte (48 digits)
Data holding time without charging: 5–6 months.

Checking data

In a large data-collecting system such as the Swedish NFS, there is a great risk of recording incorrect data. To decrease the number of errors, and to obtain some idea of the amount of them, some arrangements have been made. The most important ones are:

- Validation tests and other tests in the micro-computer
- Tests in the Cyber computer
- Check teams
- Inspections.

Tests in the computers

The validity of all variables recorded in the micro-computer is tested. Other tests are more advanced and need simultaneous knowledge of the value of more than one variable. Today a few such tests are made in the micro-computer. Most tests are made in the central computer. The test program contains several hundred tests. When an error has been discovered, an error-message is written, together with a list which contains data recorded on the tract. These lists are sent by post to the team for correction. The team makes the corrections on forms, which are returned. The correct values are then entered into the central computer.

Checking-teams

To get an idea of the reliablility of the measurements and estimates in the survey, there has been an independent check-inventory of approximately five per cent of the sample plots. This inventory, which has been going on since 1968, is now performed by two checking-teams.

The checking-teams work independently of the ordinary survey, though they record differences in the measured variables (e.g. number of trees that has been calipered) and inform the ordinary teams if the differences are too great.

Inspections

A special field inspector visits each team 2–3 times each season in order to discuss difficulties in the work, etc.

Integrating information to an inventory system

Field tests

The full-scale application of the new survey was preceded by two pilot studies, one in 1981 and one in 1982.

The purpose of the pilot studies (Jonasson, 1982) was to see how the new methods worked in regard to equipment, definitions of different variables, time consumption for different procedures, etc. The survey of 1981 was performed during four weeks by two crews consisting of three persons each. The test included both permanent and temporary tracts with 10 and 14 plots, respectively. The radius of the plots were 10 (permanent) and 7 (temporary) metres, respectively. On some of the tracts a reinventory was performed two or three months after the first inventory.

A time study was carried out comparing the time spent on temporary and permanent plots. The average difference in total time per plot was 12 minutes. Looking at separate time elements, calipering took about five minutes longer on a permanent plot. On permanent plots, calipering includes assigning polar coordinates to all trees with a diameter at breast height exceeding 4 cm. The permanent plots are twice as large as the temporary plots. The difference is rather small, perhaps due to random errors because of the low number of plots included in the study.

Eight permanent tracts were reinventoried. To make it easier to find the plots, the teams had information on the tract, including plot maps with the positions, species and diameters of the trees.

It was rather easy to re-locate the starting points and the plots (partly because of the short time between the two inventories). The map made it easy to find every single tree on the plots, and to discover faults that had occurred.

The time study showed that, compared to the inventory earlier in the summer, the reinventory took 5 minutes less per plot. This was to a large extent due to fewer tasks during the reinventory.

The tests in 1981 showed that it was possible to carry out a forest survey of this type with crews composed of three persons, but not in one day with the design used. This fact, together with statistical considerations, resulted in a reduction of the number of plots from 14 to 12 on the temporary tracts and from 10 to 8 on the permanent tracts.

The last field test, the test of 1982, was composed of two teams working 4 months each. A new feature of this test was to find out how easy or difficult it is for a rather inexperienced person to do the job. It was also of great value to get different views. Therefore the team members were successively replaced. In all, 7 crew leaders and 9 other crew members worked in the test. Some of them had earlier worked in the NFS.

As there are varying conditions in different parts of Sweden, the field test covered the whole country.

From this test we learned that the average working times on the temporary tracts were longer than on the permanent tracts. Moreover, surveying the tracts took, on the average, too long. One likely reason for this is that the members of the crews were replaced. It always takes time before a new member has learned the routine.

These facts led to some modification of the design.

Full-scale application

The new NFS was introduced on a full scale in 1983. Before the field season, a comprehensive education program was carried out, in order to prepare the survey crews as well as possible. Over-all, experience of the field work was favourable. Even if the differences in efficiency and accuracy between different teams were considerable, on average the working time was shorter and the number of errors per tract less than "just acceptable". Especially the introduction of a new data recording and testing system was successful.

However, some of the new variables proved to be unsuitable. For example, it seems difficult to judge the number of trees per hectare in stands which do not have a very regular structure. Most of the variables appeared, however, to be well chosen and defined from the point of view of field-work.

Permanent and temporary tracts as designed here demand about the same working time. However, the site specialist acted as such on the permanent tracts, while he was an ordinary team member on the temporary tracts. This means that the NFS required three persons in the crew on permanent tracts, four on temporary. The working time varied more with forest conditions on permanent tracts than on temporary ones.

The introduction of micro-computers for data recording and preliminary testing was very successful. This system facilitated the field work, made it less weather-dependent and also considerably reduced the number of errors detected in the checking programs at the office. As it is much better to correct data directly at the time of measurement in the forest than one or two weeks later—which is the routine for errors detected at the office—this means an improved data quality. The equipment used—weatherproof, sealed micro-computers, solid-state memories and transmission equipment—proved to be very reliable.

During the summer of 1983, 24 teams worked for a total of approximately 2 000 days inventorying the Swedish forests. The frequency of malfunctions was about 2 per mille. The transmission worked properly and 15 000 000 characters were transmitted to the main computer.

The errors made by the inventory personal were reduced from 35 000 to 13 000, mainly because of the new data acquisition system.

No team was delayed for more than a few hours as a result of trouble with the equipment. This is a better outcome than expected, and it is evident that the pen-and-paper period of field data recording has come to an end in our NFS.

Discussion

The new Swedish NFS and some preparatory studies have been reported. The paper now concludes with a discussion of the expected accuracy and some ideas for the future.

Using mathematical models of the type described earlier, and data collected during the period 1973–77, it has been possible to compare the precision in the new design with the precision in the "1973-design".

Since a permanent tract has a shorter side length and fewer plots than a temporary tract, the permanent tract is not, before the first reinventory, as informative as the temporary tract. When estimating volume/ha or area forest land, 1 000 temporary tracts and 1 300 permanent tracts will yield the same precision.

In Hägglund (1983) a comparison of the precisions obtained in the new and the "old" inventories are given for volume/ha, area forest land and total volume. Here we only compare the precision in the estimates of total volume.

After the first reinventory, the total volume was

Table 7. *A comparison of the precision when estimating total volume*

County or part of county	Coefficient of variation, % 1973–77	1983–87	1988–92	1993–97
ACL	3.8	3.8	3.3	3.0
ACK	3.3	3.3	2.7	2.5
Y	2.5	2.7	2.3	2.1
X	3.0	3.0	2.5	2.3
F	3.5	3.5	3.0	2.7
U	5.3	5.2	4.5	4.2
M	10.8	8.1	7.7	7.1
L	5.2	4.2	3.9	3.7

Remark: In the period 1983–87 the permanent plots have not been reinventoried; in the period 1988–92 they will be remeasured once and in the period 1993–97 they will be remeasured twice.

Table 8. *A comparison of the 1973–82 survey and the survey which started in 1983*

Region	Number of tracts on land/year		Number of volume plots/year		Surveyed area, ha/year	
83+	73–82	83+	73–82	83+	73–82	83+
1	210	236	2 520	2 360	74	52
2	360	402	4 320	4 020	126	88
3	222	270	2 664	2 700	85	59
4	457	560	5 484	5 600	176	123
5	203	2×319	3 248	3 828	96	80
Total	1 452	1 787	18 236	18 508	557	402

already estimated with a substantially higher precision than if temporary tracts only had been used. However, the great gain in precision was obtained in the estimates of changes. The change in volume during a period of 5 years is estimated with a standard error which is about one half of the standard error obtained with a design based on temporary tracts only. It is interesting to relate the results in Table 7 to the number of tracts, number of plots and surveyed area in the two surveys.

Looking forward, the new design will mean that we have lost some flexibility. In order to obtain the advantages connected to the permanent plots, we have to keep the design for at least 10 and probably 20 years. This means that the nearest years will be devoted to consolidating and refining the present design. Some new questions have to be investigated, however:

- The monitoring of tree damage caused by air pollution will be intensified. Special investigations of this question are already going on.
- The possibility of using satellite images in the NFS must be investigated in detail. For example, the new Landsat and Spot satellites give much more detailed information than the old satellites. Even if this information is expensive, it might pay to use it if the number of temporary tracts could be reduced in this way.
- The development of micro-computers is very rapid and there will most likely be new and more cost-effective equipment available in a few years. There must be a continuous follow-up and adaptation to new techniques.
- As mentioned earlier, some type of coordination with rough stand data obtained in the nation-wide ÖSI-inventory is a possibility in perhaps 10 to 15 years. This could be of mutual interest for both inventories.

Further, there will continually occur new questions in forestry, questions which need a fast elucidation through a few years' survey data. This implies that there will always be changes in the survey, but we hope and believe that the new basic design and fundamental variable set will form a stable basis for Swedish national forest planning for the next two decades.

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Appendix

Sampling with partial replacement

In this appendix the difference between the non-random and the random approach will be illustrated. We consider, for simplicity, a situation where we have the following observations:

- $T(1)$ temporary plots measured in year 1
- $P(1)$ permanent plots measured in year 1
- $T(2)$ temporary plots measured in year 2
- $P(2)$ permanent plots measured in year 2
- $T(3)$ temporary plots measured in year 3
- $P(3)$ remeasurement of the permanent plots from year 1
- $T(4)$ temporary plots measured in year 4
- $P(4)$ remeasurement of the permanent plots from year 2.

Thus we have 6 different samples which we assume to be independent.

Suppose that we want to estimate current volume/ha in year 4. We construct the following three estimates.

I: $T(4)$
II: $P(4)$
III: $T(2)+(P(4)-P(2))$

The final estimate is obtained by forming a weighted mean of these estimates. The weights are chosen so that the variance is minimized. We assume that the design used is such that $\mathrm{Var}(T(i))$ is independent of i and the same is true for $\mathrm{Var}(P(i))$. The variances are denoted by $V(T)$ and $V(P)$, respectively. Furthermore, we denote the correlation between the two measurements on the permanent plots by ϱ. Then the minimum variance estimator, which we denote by y_4, is given by

$$y_4 = a_1T(4)+a_2P(4)+a_3(T(2)+P(4)-P(2)),$$

where

$$a_1 = 1- \frac{V(T)(V(P)+V(T))}{(V(P)+V(T))^2-\varrho^2V(P)^2}$$

$$a_2 = (1-a_1)(1- \frac{\varrho V(P)}{V(T)+V(P)}$$

$$a_3 = (1-a_1) \frac{\varrho V(P)}{V(T)+V(P)}.$$

Proceeding in the same way we get best linear unbiased estimators y_1, y_2 and y_3 of the volume/ha at year 1, 2 and 3, respectively. We gather the estimators obtained in the vector

$$Y= \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}$$

Since the design is symmetric between years, the covariance matrix Σ of Y has a very nice form:

$$\Sigma = \begin{bmatrix} v & 0 & c & 0 \\ 0 & v & 0 & c \\ c & 0 & v & 0 \\ 0 & c & 0 & v \end{bmatrix}$$

As soon as the weights a_1, a_2 and a_3 are determined we easily calculate

$$v = a_3^2(V(T)+V(P))+(1-a_1)^2V(P)+a_1^2V(T)-2a_3(1-a_1)\varrho V(P)$$

and

$$c = 2a_1a_3V(T)-2a_3(1-a_1)V(P)+\varrho V(P)((1-a_1)^2+a_3^2)$$

In the calculations above we have assumed that ϱ, $V(T)$ and $V(P)$ are known. In practice we either have