2 Methods

2.1 Inventory Concept NFI2

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2.1.1 Introduction

The inventory concept of the NFI links data that were assessed through field surveys, aerial photography interpretation, inquiries and map interpretation, and the informational needs, which were intended to be satisfied with the NFI. Inventory methods are subject to change, since informational needs and technical possibilities of data survey underwent a change through the course of time. In the first NFI, the main objective of the survey was to describe the state of the Swiss forests. This description, which has the nature of a snapshot, was also required in the second NFI. In addition, the changes had to be presented, which took place in the Swiss forest in the ten years between the first and successive inventories. These new problems made further development of the sampling concept of the NFI indispensable.

In the first NFI, only rough data on the Swiss forest (of which the reliability was partially unknown) was available for the method development. The method development for the second NFI was able to use the rich experience obtained during the conduction and data analysis of the first NFI. These experiences affected first, the inventory practice and second, the findings about the Swiss forest itself. The results of the first NFI survey allowed a better understanding and definition of the sample population (the Swiss forest) with respect to the variability and the spectrum of quantitative characteristics. With this information, it was possible to develop a more efficient method, which was better fit to the population.

Apart from the newly developed approach to describe change, the most important method modification affected the deployment of aerial photographs. In the first NFI, aerial photographs were used for the first time to cover the entire country of Switzerland in the framework of forest surveys. At that time, comparable surveys were only available for small (test) areas and applications at the regional or even on the national levels were hardly known. Aggravating for the employment of aerial photographs is the diversity of the Swiss forest, which is characterized through heterogeneous, small area structures and, consequently, was particularly demanding to the inventory methods. The second NFI was able to build on the experience of the deployment by completely covering aerial photographs in the first survey. Accordingly, by developing this method further, it became the pioneering role in Europe.

The efficiency of the NFI was significantly improved because of the intensive utilization of aerial photographs and the development of new methodological approaches that combined data derived from aerial photographs and forest samples. Especially attractive was the reduction in the number of forest samples by approximately 50 percent, while at the same time keeping the estimation precision of the first NFI for all of Switzerland and the five production regions. Due to the reduction in the field survey, each of the forest samples in the second NFI increased in weight. The reduction of the field survey was only possible because special analysis within the first NFI, along with the pilot inventory for the second NFI, revealed the high data quality of the field survey. A revised inventory manual (STIERLIN *et al.* 1994), an intensive training plan, and an independent control survey guaranteed high data quality in the second NFI (see Chapter 2.8 and 2.9). It also reduced the danger of one-sided error to a minimum. The high quality data that was guaranteed by the field survey formed the basis for efficiency improvement through the intensive aerial photograph deployment.

Even though the statistical methods fundamentally changed, the second NFI proceeded with high continuity from the first one. For example, the data sources of the first NFI were also kept in the second NFI, and the concentric sample plots and quadratic interpretation area of the field survey were not changed. In addition, the sample selection followed in accordance with the sample grid of the first NFI. All data from the first survey was used in the analysis of the second NFI.

The development method of the second NFI was guided by two important principles: The methods were only modified as far as it was absolutely needed, and the selection of the statistical methods, simplicity, and universal validity were ultimately given preference over more complex procedures, which would have only gained efficiency for a few characteristics. Many statistical approaches were tested during the development of these methods. For example, geostatistical methods (KÖHL and GERTNER 1992), Bayes estimators (KÖHL and GREEN 1991) and successive inventory designs with partial replacement of sample plots (SCOTT and KÖHL 1994). Under special conditions and for specific problems, these procedures led to more efficient estimates; however, they could not be combined into a universal valid sampling design for the second NFI. For the final determination of the sample designs of the second NFI, a more robust procedure was preferred, which was not only applicable to a few key characteristics such as timber volume or increment, but was also applicable to all conditions which could be encountered in the Swiss forest. That the procedure also led to immediately understandable results and additive tables was a nice concomitant.

In the following, an overview is given about successive inventory concepts and multi-phase sampling techniques to combine data observed from aerial photographs or on sample plots. Following, an account for the sampling concept of the second NFI and a discussion of the procedures to optimize the sampling design is given.

2.1.2 Sampling Procedure for Successive Inventories

The idea of describing the development of stands through permanent observations and thereby controlling the sustainable forest management was born in the last centennial in Europe. In Germany, permanent plots were already set up in 1860 (GRAVES 1906). In France, GURNAUD (1878) developed rules to use successive measurements to estimate increment, which are known as control method (Kontrollmethode, méthode du contrôle). BIOLLEY (1921) was the first to apply these rules. The forest of Couvet in the Swiss Jura, where the methods were developed, was measured ten times between 1890 and 1946 in intervals every six to seven years. Therefore, the permanent forest observation has been a 100-year tradition in Switzerland.

2.1.2.1 Continuous Forest Inventory (CFI)

In the United States, the idea of permanent observation became more important because of the economic recession between 1929 and 1950 (STOTT and SEMMES 1962), and thereby increased interest in primary production factors. Directly applying the European methods, which were based on recording all trees within a stand, especially the control method of GURNAUD (1878) and BIOLLEY (1921) was not possible. The vast areas of the North American forest would only allow the survey of a small part of the forest of interest. A solution to this dilemma was presented in the application of sampling methods that was rarely practiced at that time.

In the 1930's, sampling methods known as Continuous Forest Inventory (CFI), were developed which were based on repeated measurements of a set of sample plots (STOTT and RYAN 1939). STOTT and SEMMES (1962) give a historic overview of the CFI application. In the Midwest, between 1937 and 1938, a few hundred permanent sample plots in forests operated by the wood processing industry were established. In the Great Lakes and Central Plains States starting in 1939, approximately 3,700 permanent circular sample plots were set up in private, industrial and public forest enterprises. In 1948, the inventory of forests in Ohio and Wisconsin took place with about 1000 permanent sample plots. In 1952, the American Pulpwood Association (APA) became aware of the CFI and introduced it to their members. During the following years, a cooperation between the APA and the USDA Forest Service led to an extensive application of the CFI extending east of the Mississippi River. In 1962, approximately 50 enterprises associated with the wood processing industry managed 25 million acres using the CFI method.

In Germany in 1936, KRUTZSCH and LÖTSCH (1938) set up permanent sample plots for a continuous yield control. In Sweden, a similar concept was developed by PATTERSON (1950) and was applied in the forest yield research at the Swedish forest experimental station. In Switzerland, SCHMID (1967) introduced the CFI into forest management planning and advanced the classical control method to the continuous forest inventory. His intensive effort toward an applied survey method for permanent sample plots (SCHMID-HAAS *et al.* 1993) resulted in a wide acceptance of the method in Swiss forestry.

With the CFI method, all sample plots measured at the first occasion are measured again in successive inventories. The estimated mean of an attribute (e.g., growing stock, number of trees, basal area) and its variance are estimated as follows:

$$\hat{\bar{\bar{Y}}} = \frac{\sum_{i=1}^{n} Y_i}{n} = \text{mean on second occasion} \tag{1}$$

$$\hat{\bar{\bar{X}}} = \frac{\sum_{i=1}^{n} X_i}{n} = \text{mean on first occasion} \tag{2}$$

$$v(\hat{\bar{\bar{Y}}}) = \frac{\sum_{i=1}^{n} (Y_i - \hat{\bar{\bar{Y}}})^2}{n(n-1)} = \text{variance of } \hat{\bar{\bar{\mathrm{Y}}}} \tag{3}$$

$$v(\hat{\bar{\bar{X}}}) = \frac{\sum_{i=1}^{n} (X_i - \hat{\bar{\bar{X}}})^2}{n(n-1)} = \text{variance of } \hat{\bar{\bar{\mathrm{X}}}} \tag{4}$$

where

Y_i = observation on sample plot i (i = 1, ... n) on second occasion
X_i = observation on sample plot i (i = 1, ... n) on first occasion
n = number of sample plots ($n = n_1 = n_2$)

Changes between two occasions can be derived through the difference of both means.

$$\hat{\bar{\bar{G}}} = \hat{\bar{\bar{Y}}} - \hat{\bar{\bar{X}}} \tag{5}$$

The change G (= growth) has the variance

$$v\left(\hat{\bar{\bar{G}}}\right) = v\left(\hat{\bar{\bar{X}}}\right) + v\left(\hat{\bar{\bar{Y}}}\right) - 2\,r_{yx}\sqrt{v\left(\hat{\bar{\bar{X}}}\right)}\sqrt{v\left(\hat{\bar{\bar{Y}}}\right)} \tag{6}$$

where
r_{yx} = correlation coefficient between the observation on the second occasion and the first occasion.

The higher the correlation is between observations, the smaller the variance of the difference is. The value of the correlation coefficient r_{yx} decreases with increasing time intervals between observations. If completely independent sample plots are measured on both inventory occasions, the last term of (6) is dropped for calculating the variance. Consequently, the CFI estimator always produces a smaller variance than independent observations. This is also true when the correlation of the observed values is small on both occasions. The advantage of using the CFI method is clearly in the reduction of the variance of estimated change. The variance of the state estimation is not influenced.

Apart from the described advantages of the CFI method, it also contains the danger that the position of the permanent sample plots will be known and that the management of them is changed. It was not absolutely possible to assume hidden invisible NFI sample plots for several reasons: 1) Out of 11,000 NFI sample plots, 686 were visited annually for the national forest condition survey; 2) The position of the sample plot centers is visible by color markings; 3) A part of the NFI sample plots are used for the cantonal forest condition survey; 4) The sample plot centers correspond with the grid net of the topographic maps; 5) The position of the sample plots is known to the local forest service from the questionnaire accompanying the first NFI. The danger that visible permanent sample plots are not representative for the entire population through a changed management throughout the course of time has often been described; thus, according to SCHMID-HAAS (1983), there is "no guarantee that visible samples will remain representative." He believes that even the most experienced forester cannot be sure that he would not be influenced by the knowledge that his work might be subject to scrutiny. Consciously or unconsciously, it is possible that the sample areas are being treated differently than the rest of the standing timber. A sample plot inventory, which cannot reliably eliminate this danger, is not very suitable for planning purposes. From this conclusion, a clear requirement for an addition to the permanent samples through temporary sample plots can be drawn, so that systematic influences are quantifiable and make it possible to adjust the estimates. (See Chapter 2.10.)

2.1.2.2 Sampling with Partial Replacement of Sample Plots (SPR)

A sampling method for field survey that was introduced in the 1960's to the applied forest inventory is Sampling with Partial Replacement (SPR). With this method, portions of the sample plots that are measured in the first survey are replaced by new samples. For two occasions three types of sample plots can be considered:

- Sample plots, which are measured on the first occasion as well as on the second occasion (permanent sample plots, matched plots, n_{12} sample).
- Sample plots, which are only measured on the first occasion (unmatched plots, n_{1-} samples).
- Sample plots, which are only measured on the second occasion (new plots, n_{-2} samples).

If only the net change has to be estimated (e.g., volume growth), permanent sample plots are more cost efficient than two independent surveys. This means that for the same cost they lead to a smaller sample error. This seems obvious, since the difference between two independent observations is not only caused by change alone, but also through the variation within the two populations. If only current state is to be considered, temporary sample plots are often shown to be more cost effective than permanent plots, since the expenditures for marking the sample plot centers and the registration of sample tree coordinates do not exist. Combining both of these sample plots can therefore improve the cost efficiency, while at the same time, current state and change are to be estimated.

The estimators introduced in the following are calculated in four steps:

(1) At first the successive measurements on the second occasion are related through a simple linear regression with the values on the first occasion. Through this regression, the values of the sample plots that are not remeasured are updated. To describe the current state, two means are calculated: One mean is based on the measurements of the matched plots and the updated values of the unmatched plots. A second mean is derived from the new (temporary) sample plots.
(2) For both means the variance is calculated.
(3) Through weighting both means with their inverse variance, a combined estimator is derived. If the regression estimator has a larger variance, it receives a lower weight and vice versa.
(4) As the last step the variance of the combined estimator is calculated.

These steps can be used for the estimation of the current state, as well as for the estimation of the net change.

Apart from others, SUKHATME *et al.* (1984), COCHRAN (1977), and KISH (1965) also discuss the theory of sampling with partial replacement of sample plots. BICKFORD (1956) was the first to introduce the theory of SPR to the forest inventory applications. The first application of SPR was done in an inventory conducted by the USDA Forest Service in the northeastern United States. BICKFORD (1959) combined SPR with aerial photographs and applied this modified method in the Allegheny National Forest.

WARE (1960) examined the data of repeated measurements in the northeastern region of the United States and found that in six out of eight cases the variance was not the same at both inventory occasions. If the algorithm which calculates the SPR estimator ignores this fact it would result in biased estimates.

WARE and CUNIA (1962) decisively extended the applicability of SPR. Until the derivation of the theoretical framework, the application of SPR was limited to only a few special cases, since the sample theory for SPR requires either the equality of population variance, the same sample size of succeeding inventories, or the satisfaction of both requirements. The problem of the optimal strategy for replacing the sample units was only solved for the case of the estimation of one attribute. Furthermore, different survey costs for new and repeated measured sample plots were not accounted for.

SCOTT (1981; 1984) derived estimators from the sample values, which completely use the variance information of the permanent and temporary sampling units. He applied the variance estimator derived by MEIER (1953), which estimates the weights from the sample values, as well as the variance of the regression estimator for a two-phase sample. SCOTT and KÖHL (1994) extended SPR in the two-phase sampling for stratification at two and three occasions.

A detailed description of the work about SPR is found in KÖHL (1994), who additionally shows that the application of the SPR estimator has its problems. After more than two inventory occasions, the SPR estimator becomes very complex and unwieldy (SCOTT 1986; 1994). At the second inventory occasion, three different types of sample areas must be distinguished: permanent samples, new samples, and old samples. With three inventory occasions, there are already seven different types of sample plots. Therefore, the complexity increases with the number of observations in time.

Inventory results are not only needed for the entire population (i.e., the entire forest area of Switzerland), but also for thematic subunits, such as the forest area structured by property categories according to site quality. Out of these demands, results have been presented in table form. In the table margins, the total value for the thematic subunits of the columns and rows is found. In the case that the cell and marginal values of tables are estimated independently of each other, the cell values will not add up to the column and row sums (see Table 1). Non-additive tables are not a problem for the statistician. Nevertheless, they are hardly accepted by the users of the inventory results. Consequently, the non-additive tables have to be adjusted. Different methods were developed for adjusting the non-additive tables. These procedures are very complex and can result in biased results within individual cells.

Table 1a. Example for an additive table.
Forest area by type of ownership and site quality in 1000 ha.

	poor/moderate	good/ very good	Total
Public forest	404.1	408.0	812.1
Private forest	114.5	259.7	374.2
Total	518.6	667.7	1186.3

Source: EAFV 1988, page 81.

Table 1b: Example for a non-additive table.
Forest area by type of ownership and site quality in 1000 ha.

	Poor/moderate	good/ very good	Total
Public forest	409.1	407.0	824.9
Private forest	119.4	256.8	370.3
Total	503.1	671.9	1186.3

The application of the CFI method can also lead to problems. The inventory systems are dependent on whether the permanent samples are representative. This is especially true in managed forests or in the event of changing landuse. A change in the inventory objectives cannot be taken into account when changes of sample sizes or locations of sample plots are required to meet the new objectives. However, applying the CFI estimator results in additive tables.

The problem encountered with the application of the SPR method led some survey regions of the United States to replace the SPR method with alternative sampling designs (HAHN, SCOTT, personal communication).

In the Swiss National Forest Inventory, CFI as well as SPR estimators were used. During the second survey, only 50 percent of the forest samples from the first NFI were remeasured (permanent samples), and about 600 sample plots were newly set up (new samples). In order to estimate current state, only new and temporary samples were used. The estimation of change was based only on the permanent samples. Thus, the CFI estimator for the derivation of change, and the SPR estimator for the derivation of the current state were combined. The integration of both approaches in the two-phase NFI concept, which was based on aerial photography interpretation and terrestrial survey, is described in Chapter 2.1.4.

2.1.3 Combined Inventory Procedures

If sample plots lie far apart from one another and can only be reached at great expense, it could be very costly to survey the inventory area through randomly or systematically distributed terrestrial sampling units. In the statistical literature, sampling methods can be found which can dramatically increase the efficiency of a survey by utilizing information from several different data sources. If these procedures are applied to forest surveys, it is suitable to combine terrestrial measurements and interpretation of aerial photograph or satellite data. Combined surveys utilizing aerial photography and field assessments were already intensively studied in the 1950's (HILDEBRANDT 1961, 1962). HILDEBRANDT gives an overview of the state-of-the-art research and applications of combined forest surveys at that time.

The production of maps showing the distribution of forests has always played an important role in the employment of aerial photography in forest management. Today, capturing the forest area dynamics in densely populated areas and in regions of the tropical rainforest or boreal forests is of the utmost importance. The suitability of aerial photography and digital remote sensing data to monitor forest area change has been intensely studied (see for example ITTEN *et al.* 1985; KUSHWAHA 1990) and is in some countries, such as India (UNNI 1990), an already routinely applied standard forest area monitoring method. Nevertheless, this aspect of applied remote sensing methods shall not be discussed any further here.

The following discussion focuses mainly on the application of aerial photography for the growing stock estimation. The following three conceivable groups of sampling designs for combined forest inventories are illustrated further:

1. Stratified sampling
2. Multi-stage sampling
3. Multi-phase sampling/double sampling

The multi-phase/double sampling group can be further divided into:

3a. Double sampling with regression estimators
3b. Double sampling for stratification
3c. Double sampling for stratification with regression estimators

Stratified sampling is based on the partition of a population into several homogenous non-overlapping subunits – so called strata. Because of the decomposition of the total variance into the variance within the strata and between the strata, the sampling error is smaller than compared to a simple random sample of the same sample size. A prerequisite for the application of stratified sampling is that the size of the strata must be known. Aerial photography can be used with the stratified sampling design to determine the size of each individual stratum. The boundaries of areas with homogenous structure are hereby recorded (delineated), and each area (parcel) is assigned to a stratum. Subsequently, the size of the individual strata is calculated by adding the parcels together. High labor and time expenditure for implementing stratified sampling is inevitable because of the necessity to delineate the strata and the subsequent area calculation that follows. The application of a stratified sampling design does not seem appropriate for large-scale inventories when aerial photography is used for stratification.

A clearly organized illustration of multistage sampling designs for forest inventories can be found at BOWDEN et al.(1979) and JOHNSTON (1982). They give examples of up to four stages by employing terrestrial surveys, samples on aerial photographs and classification of digital satellite data. LANGLEY (1975) showed the application of multistage sampling designs with unequal selection probabilities. He gives different inventory examples with up to five stages and combines terrestrial measurements, aerial photography, and space images from Apollo 9.

In a double sampling design, the auxiliary variable is assessed in the first phase (survey stage), while in the second phase the variable of interest is assessed. The auxiliary variables should be easier and more cost efficient to be assessed than the target variable, since more samples are taken in the first phase than in the second one. Usually, the double sampling design permits a more cost efficient assessment of the variables of interest than the simple terrestrial survey for the same level of precision.

For combined inventories to estimate the growing stock, remotely sensed information (e.g. from aerial photographs) is utilized in the first phase. In the second phase, the survey of timber volume takes place by measuring individual trees on forest plots.

The term “double sampling with regression estimators” applies when the growing timber is estimated e.g. in aerial photographs, or when variables are estimated which are correlated with the growing stock and are further related to the measured standing timber in the forest sample plots via a regression estimation. The interpretation of aerial photography can also serve to determine the size of the strata and can be used for the derivation of the measured growing stock for each individual stratum. This procedure is called “double sampling with stratification”, whereby poststratification is applied. A multitude of publications exist which deal with estimating growing stock with double sampling designs. In German speaking regions, double sampling with regression estimators was mainly studied.

The applications of combined inventories described in the literature are dominated by double sampling with regression estimator. The suitability of the procedure is usually investigated in smaller regions (e.g., southern Black Forest, Lüneburg Heath, or Harz), in homogenous forest areas, or with the help of large-scale aerial photographs (1:3000 to 1:10000). The variable of interest is nearly always timber volume. Applications of the double sampling for stratification are also found to be used for large scale surveys in such regions as Lappland (POSO 1972), North America (BICKFORD *et al.* 1963) or India (KÖHL 1991).

There could be several reasons for the hesitant application of the double sampling with regression estimators outside of special studies. The efficiency of this procedure depends on the cost relationship between the assessment in the first and second phase, and it also depends on how tightly the relationship is between the variable of interest and the auxiliary variable. In large areas or in forests with a large spatial variability, R^2 values of 0.4 seem to be realistic, while in homogenous or small-scale forest areas, a relatively high R^2 value can be obtained. R^2 values larger than 0.9 nevertheless seem questionable and are very often the result of transformation or of regression through the origin. The interpretation of R^2 values in these cases is critical.

Attributes measurable in aerial photographs such as tree height, crown diameter, or the number of trees within a defined area could be used as independent variables in a regression function to estimate the growing stock. These regression functions have the distinct disadvantage that the independent variables can only be determined in the aerial photography under sometimes unrealistic conditions. Apart from a suitable aerial photographic scale – SCHADE (1980) believes that a scale of 1:10,000 is too small to determine the crown diameter –

the stand conditions must allow for the measurement of the variables. In dense, multilayer forests, the assessment of the number of trees or the crown diameter is difficult, and in fully stocked stands the direct measurement of tree heights is impossible. Consequently, a double sampling design, where the auxiliary variable is based on volume functions derived from measurements in aerial photographs, is for many practical applications not feasible.

The quantification of the entire growing stock for large-scale forest inventories is usually only one of many attributes to be assessed. Detailed representation, in respect to the growing stock (for example, ordered by development stages and tree species) requires the evaluation of subunits, which are summarized in tables. For each of the subunits, a new regression relationship has to be derived independent from each other, which – similar to the problem with SPR – leads to non-additive tables. The necessity to derive such a multitude of regression relationships and the adjustment of the tables, as well as the demand for detailed results of forest inventories, result in the analysis of double sampling methods with regression estimators becoming very complex and awkward. Since regression analysis depends on certain assumptions, not all target variables can be analyzed. This is especially true for variables on a nominal or ordinal scale. Double sampling with regression estimators is, therefore, only applicable to the analysis of very few requested attributes of interest for a forest inventory.

An implicit requirement for the application of regression analysis is the assessment of the variable of interest and the auxiliary variable on the same object, and results in the constraint that the sample plot centers of aerial photographs and terrestrial plots must coincide.

Studies of the position accuracy in the NFI have found that the center of the aerial photo plots and the terrestrial sample plots are, on average, five meters apart. Since the terrestrial samples in the first NFI were located with high expenditures, it is reasonable to assume that the distance achieved here is the lowest limit possible under practical conditions. Further distances should be expected, especially in inaccessible forests. In tropical forests these sample plot centers rarely coincide. A tight relationship between the auxiliary and target variable cannot be expected because of the forest's large-scale homogenous structure and highly variable structures in small areas.

The method of double sampling for stratification utilizes an auxiliary variable, which serves to estimate the strata size. Measurements in aerial photographs can be simplified, so that the cost for the first phase sample can decisively be reduced, as compared to double sampling with regression estimators. No regression functions have to be derived; the analysis of subunits leads to additive tables. Consequently, the estimation procedure is considerably more simple than for double sampling with regression estimators and is generally applicable.

Samples do not necessarily have to coincide, as long as the samples from the first phase and the samples for the second phase are ensured to be in the same stratum. Errors in the interpretation do not lead to biased results, but to a higher variance within the strata and, thereby, to a higher sampling error. If the interpretation of the auxiliary variable includes a class "non-forest", the results of the photography interpretation can directly be used for area estimation.

When the growing stock is estimated, the efficiency of the double sampling for stratification design could be smaller than the double sampling with regression estimators' design. Because the analysis algorithms are far easier to manage, the applicability for continuous and non-continuous data is warranted, and the implementation of the method is also possible under difficult, practical conditions, double sampling for stratification can be considered a robust procedure. It is preferred for large-scale, multi-resource inventories with a multitude of objectives.

2.1.4 Statistical Design of the Second NFI

Before the statistical aspects of the NFI sampling concept are described (detailed account in KÖHL 1994), the notation used in the following is briefly introduced. For periodical surveys, the number of sample plots which are measured on different inventory occasions are termed as follows:

First occasion:
n_1 = Number of sample plots that are measured on the first occasion.
Second occasion:
n_{1-} = Number of sample plots that are measured on the first occasion.
n_{-2} = Number of sample plots that are measured on the second occasion (new samples).
n_{12} = Number of sample plots that are measured on both occasions (permanent samples).

The minus sign indicates that a sample plot was not surveyed at any particular point in time. From this notation, it is clearly obvious when a sample plot was surveyed for the first time. Figure 1 illustrates the different types of sample plots.

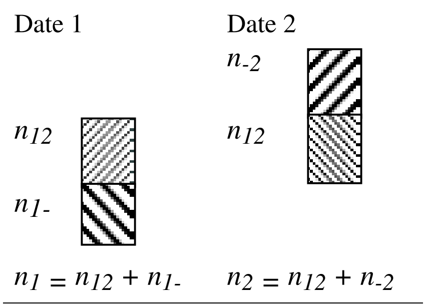

Figure 1. Types of sample plots for two inventory occasions.

Attributes, which refer to the entire population (all trees in the Swiss forest) are noted with capital letters, or rather Greek letters. Estimators derived on the basis of samples are represented by small letters, or with the symbol “^”. Different capital letters distinguish different attributes accordingly. Occasions are also distinguished when these attributes are measured. The index *i* refers to sample plots. Index *j* refers to individual trees.

2.1.4.1 Area Estimation

Information about the area and area proportion presents a central result of forest inventories and is important for the following three topics:

1. The area itself is an important target parameter for forest inventories. Apart from the quantification of the entire forest area, detailed accounts of the areas size are necessary (i.e., the size of forest types, tree species or age classes).
2. Many estimators of forest inventories are area related, such as the growing stock per hectare.
3. Quantifying the forest area change is of the utmost interest in regions with strong forest area dynamics.

Area estimations have basically two different target parameters: the amount of area (i.e., forest area proportion) and the absolute area (e.g., forest area). The absolute area calculated by dot grids depends on the number of dots that fall into the appropriate category. The area proportion always has to be seen in relation to the total area. The estimation of proportions with random points is statistically very easy. The localization of one point corresponds to a Bernoulli experiment with the possible values of non-forest and forest. The Binomial distribution describes the sampling design completely: If n_W out of n random points are found in the forest, $p= n_W/n$ is an unbiased estimator for the true forest proportion p. In the estimation of the total area, the sample points are realizations of a Poisson process with a density λ, where each point represents on average an area of $1/\lambda$. An estimator for the area F is given by $F=n/\lambda$. For additional information see KÖHL 1994.

For the NFI, the forest area and the forest area proportion was estimated from aerial photographs. A careful illustration of the aerial photography interpretation, as well as the forest definition of the NFI, can be found in Chapter 2.2. On a sample grid with a mesh width of 500 meters, aerial photo samples were distributed over the entire country, and each sample point was decided to be either forest or non-forest. On the basis of this dot grid, the total forest area and the forest area proportion were assessed. The forest area proportion is estimated according to COCHRAN (pp. 50-- 1977) by:

$$p = \frac{n_w}{n} \tag{7}$$

$$v(p) \;=\; s_p^2 \approx \frac{pq}{n} \tag{8}$$

$$s_p = \sqrt{v(p)} \tag{9}$$

where

p = Forest area proportion.
q = $1-p$ = Proportion of non-forest area.
$v(p)$ = Variance of p.
s_p = Standard error of p.
n = Number of all dots on the dot grid.
n_W = Number of forest dots on the dot grid.

The total forest area $\hat{A}_w$ is estimated by multiplying the (known) total area A with the forest area proportion p.

$$\hat{A}_w = \frac{n_w}{n} A = pA \tag{10}$$

with the variance $v(\hat{A}_w)$ and the standard error $s(\hat{A}_w)$

$$v(\hat{A}_w) = A^2 s_p^2 \tag{11}$$

$$s(\hat{A}_w) = \sqrt{v(\hat{A}_w)} \tag{12}$$

If the estimation equations shown above are used for a systematic dot grid, the standard error is generally overestimated. The form and the spatial distribution pattern of the forest areas also influence the amount of overestimation. Nevertheless, experience shows that the binomial distribution gives acceptable results for larger areas such as production regions, as long as the areas are small compared to the sample grid, and as long as they are irregularly distributed (TRACHSLER *et al.* 1980). KLEINN (pg. 26/27,1991) shows by using systematically distributed points, that the difference between the sampling error of the area estimate and the true sampling error depends on the forest distribution and is moderately low for small-scale, fragmented forest areas. Since the forest areas in Switzerland mainly consist of small-scale structures and are characterized by heterogeneous distribution patterns, it seems justified to apply these estimation equations. However, for smaller units like forest districts, the use of empirical methods should be considered, which allows for a more precise estimation of the sampling error.

2.1.4.2 Aggregation of Individual Tree Data into Sample Area Values

The NFI uses concentric sample plots as sampling units. Trees with a DBH between 12 cm and 35 cm are tallied in an area of 0.02 hectare. Trees with a DBH over 35 cm are tallied in an area of 0.05 hectare. Since the only plots selected are those with their center in the forest, the selection probability of individual trees is determined in the NFI by two factors: first, the DBH and with that the plot size (0.02 ha or 0.05 ha) and, second, the distance of a tree to the forest edge.

For trees whose distance to the forest edge is larger or equal then the radius of the appropriate sample plot (r=12.62 m for DBH<35 cm or r=7.98 m for 12 cm ≤ DBH ≤ 35 cm), the selection probability only depends on the DBH. For trees whose distance to the forest edge is smaller than the appropriate sample plot radius, the selection probability decreases with increas-ing proximity to the forest stand edge. These different selection probabilities have to be corrected through expansion factors.

The statistical approach of the NFI assumes that the sample plots represent the smallest sample unit. Thus, individual tree values have to be aggregated for each sample plot. The aggregation is accomplished by weighting each single tree attribute Y_{ij} with the weight

$$w_{ij} = A/ a_{ij} = 1\text{ha}/a_{ij} \tag{13}$$

where ij represents the j-th tree on the i-th sample plot. a_{ij} denotes the area in hectares, which one tree represents, and allows taking different selection probabilities of individual trees for the derivation of estimators into consideration. Due to this type of weighting, the attributes of each individual tree $w_{ij} \cdot Y_{ij}$ are related to an area of size one hectare, that is they obtain the unit $[Y_{ij}]/\text{ha}$.

For sample plots which do not extend past the forest edge, the weights w_{ij} are constant for the 0.05 hectare or 0.02, respectively.

$$w_{ij} = w_{0.05} = \frac{A}{a_{ij}} = \frac{1\text{ ha}}{0.05\text{ ha}} = 20\text{, for trees on a 0.05 hectare sample plot } i.$$
$$w_{ij} = w_{0.02} = \frac{A}{a_{ij}} = \frac{1\text{ha}}{0.02\text{ ha}} = 50\text{, for trees on a 0.02 hectare sample plot } i.$$

Since the trees can be categorized as one of the two concentric sample plots, depending on the DBH, the projection factor can also be equivalently written in terms of the appropriate diameter range of the concentric samples. For the NFI, this results in:

$$w_{ij} = w_{0.05} = \frac{A}{a_{ij}} = \frac{1\text{ha}}{0.05\text{ ha}} = 20\text{, for trees with } d_{1.3} > 35\text{ cm.}$$
$$w_{ij} = w_{0.02} = \frac{A}{a_{ij}} = \frac{1\text{ha}}{0.02\text{ ha}} = 50\text{, for trees with } 12\text{ cm} \le d_{1.3} \le 35\text{ cm.}$$

The weight w_{ij} must be increased for trees that are standing on forest edge sample plots. For direct weighting, the proportion of sample area that is located in the forest area has to be determined for each of the two concentric samples. Both weights are then determined. This method leads to biased results, since the weight for all trees remains constant for either concentric sample plots, and because the individual selection probabilities are not corrected.

The different selection probabilities of the boundary trees can be accounted for by calculating the individual weight $w_{ij}=A/a_{ij}$ for each tree, which depends on the distance of each tree to the forest edge. This kind of method is called “tree concentric method” and leads to unbiased estimates. KÖHL (1994) discussed other possibilities to treat sample plots on the forest edge.

If the individual trees Y_{ij} are related to one hectare, the values can be summarized to one value Y_i for the ith sample plot.

$$Y_i = \sum Y_{ij} w_{ij} \tag{14}$$

2.1.4.3 Derivation of Total Values

For the derivation of means or totals (i.e., total growing stock), the values of the sample plots Y_i have to be summarized. For one-phase sampling designs, which were used in the first NFI, the mean $\hat{\bar{Y}}$ and its variance $v(\hat{\bar{Y}})$ can be calculated according to:

$$\hat{\bar{Y}} = \frac{\sum Y_i}{n} \tag{15}$$

$$v\left(\hat{\bar{Y}}\right) = \frac{\sum_{i=1}^{n}\left(Y_i - \hat{\bar{Y}}\right)^2}{n(n-1)} \tag{16}$$

If the area of the assessment unit A is assessed without error and is known, the total $\hat{\bar{Y}}$ and the variance of the total $v(\hat{\bar{Y}})$ can be calculated according to the following:

$$\hat{Y} = A \cdot \hat{\bar{Y}} \tag{17}$$

$$v(\hat{Y}) = A^2 \cdot v(\hat{\bar{Y}}) \tag{18}$$

If the area of the unit of reference has to be estimated by an independent sample, the sampling error of area estimation must be taken into consideration for calculating the variance of the total $v(\hat{Y})$.

$$\hat{Y} = \hat{A} \cdot \hat{\bar{Y}} \tag{19}$$

$$v(\hat{Y}) = \hat{A}^2 \cdot v(\hat{\bar{Y}}) + \hat{\bar{Y}}^2 v(\hat{A}) \tag{20}$$

where

$\hat{A}$ = estimated area of the unit of reference.

$v(\hat{A})$ = Variance of area estimation.

In the first NFI, the error of area estimation was not considered for calculating the results, even though the area was estimated by a dot grid of aerial photo samples. Due to this the sampling error for all area dependent values was underestimated.

Through the application of stratification, the efficiency of the sampling survey can be increased, as compared to the one-phase method. In stratified sampling, the population is at first divided up into non-overlapping subunits (strata). Therefore, each element can clearly be assigned to one, and only one, stratum. For the application of stratified sampling, the exact strata sizes have to be known. The selection of the elements takes place independently within the individual strata. The reasons for the application of the stratified sampling method are manifold. The desire to obtain information about the different subunits of the total population, e.g. for different production regions, could suggest the stratification. A significant advantage is the increase in efficiency that can be gained with a stratified sampling design. If a population is partitioned into several homogenous subunits, the estimation for a given sample size is more precise in comparison to a simple random sampling. The efficiency of stratified sampling is based on the decomposition of the variances. The variation within the strata has to be as homogenous as possible, while the variation between the strata should be high. The efficiency of the procedure depends on the ratio of both the variation portions.

For combined forest inventories, the stratification is carried out with data obtained by remote sensing. If aerial photographs are utilized, the stratification is executed through delineating the strata on the basis of visible features, such as mixture portion or crown coverage. After the delineation, the areas of the strata are derived planimetricly or with the help of other methods to determine the area. As it is necessary to delineate the strata and to subsequently determine the area, the high rate of work and time expenditure to conduct these methods is an unavoidable consequence. The application of stratified sampling design utilizing aerial photography appeared not to be anymore reasonable when applied to large-scale inventories. This is the main reason, in practical application, for conducting combined inventories on the basis of multistage or multiphase sampling designs.

In double sampling inventories, auxiliary variables are included in the first phase (assessment level), while in the second phase, the variable of interest is measured. An example of both of these phases is the crown diameter as the auxiliary variable and the individual tree volume as the target variable. The auxiliary variable should be easier and more cost effective to measure than the variable of interest, since more samples are taken in the first phase than in the second phase. At the same precision, double sampling usually allows a more cost-effective way of obtaining the desired results as compared to terrestrial surveys.

At double sampling for stratification, the auxiliary variable is used to assign the sample to a stratum. This sampling method is very similar to stratified sampling, but differs in that the strata sizes are estimated in comparison to the actual known strata size. However, the error, which arises in estimating the strata, has to be considered in the derivation of the sample error.

If the area of the inventory region A is assumed to be known, the total of an attribute $\hat{Y}_{ds}$ can be calculated through the means of the sample plot $\hat{\bar{Y}}_{ds}$. According to RAO (1973), it follows that:

$$\hat{\bar{Y}}_{ds} = \sum_{h=1}^{L} \frac{n'_h}{n'} \hat{\bar{Y}}_h \tag{21}$$

$$v(\hat{\bar{Y}}_{ds}) = \sum_{h=1}^{L} \frac{n'_h - 1}{n' - 1} \frac{n'_h}{n'} v(\hat{\bar{Y}}_h) + \sum_{h=1}^{L} \frac{1}{n' - 1} \frac{n'_h}{n'} (\hat{\bar{Y}}_h - \hat{\bar{Y}}_{ds})^2 \tag{22}$$

$$\hat{Y}_{ds} = A \cdot \hat{\bar{Y}}_{ds} \tag{23}$$

$$v(\hat{Y}_{ds}) = A^2 \cdot v(\hat{\bar{Y}}_{ds}) \tag{24}$$

where

$\hat{\bar{Y}}_h$ = mean in stratum $h = \frac{\sum Y_{hi}}{n_h}$, $h=1,\ldots,L$.

$v(\hat{\bar{Y}}_h)$ variance of $\hat{\bar{Y}}_h$, $h=1,\ldots,L$.

$v(\hat{\bar{Y}}_{ds})$ variance of $\hat{\bar{Y}}_{ds}$.

$v(\hat{Y}_{ds})$ variance of $\hat{Y}_{ds}$.

n'_h = number of aerial photographic samples in stratum h, $h=1,\ldots,L$.

n' = number of all aerial photo samples $= \sum n'_h$.

n_h = number of terrestrial samples in stratum h, $h=1,\ldots,L$.

Y_{hi} = sum of all attributes of all individual trees Y_{ij} on the i^{th} sample plot in stratum h.

L = number of strata.

The importance of stratification lies in the reduction of the sampling error, which results from breaking down the total variation into the variation within and the variation between the strata. The way the strata are formed has a considerable influence on the size of the reduction and is, therefore, not oriented on subunits which might be useful in the derivation of inventory results, but in the decomposition of the total variance, so that the variance within the strata is minimized. Since the stratification is carried out in aerial photographs, attention must be paid in order for these strata to be clearly identified and consistently recorded in the aerial photographs.

In addition to forest strata, a non-forest stratum must be included where a null value is assigned to all attributes. The error for the area estimation is thereby included in the derivation of the totals. The area of the entire forest and non-forest area of the unit of reference (productive region) is substituted for A, which is assumed to be known without any error.

The equations 21 to 24 shown above are also used for area estimation. The attribute for the area estimation is denoted by X and has two possible values:

$$X = \begin{cases} 1 & \text{if sample plot i is within the unit of interest} \\ 0 & \text{otherwise} \end{cases}$$

The area of the unit of interest $\hat{X}_{ds}$ and its variance $v(\hat{X}_{ds})$ are calculated as follows:

$$\hat{X}_{ds} = A\sum_{h=1}^{L}\frac{n'_h}{n'}\hat{\bar{X}}_h = A\hat{\bar{X}}_{ds} \tag{25}$$

$$v(\hat{X}_{ds}) = A^2 v(\hat{\bar{X}}_{ds}) \tag{26}$$

The terms of these equations are calculated by substituting Y with X in the equations presented above (15, 16, 21, and 22).

2.1.4.4 Ratio Estimator for Area Related Results

With the relationships shown up to this point, it is possible to derive totals for attributes and areas. If results are to be given in relation to unit area (e.g. per hectare), they have to be calculated by forming ratios while using total values.

For one-phase sampling designs, a ratio $\hat{R}$ of two estimates, $\hat{Y}$ and $\hat{X}$, and its variance $v(\hat{R})$ according to COCHRAN (pp. 150 seqq. 1977) is generally derived as follows:

$$\hat{R} = \frac{\hat{\bar{Y}}}{\hat{\bar{X}}} = \frac{\bar{Y}}{\bar{\bar{X}}} \tag{27}$$

and (LOETSCH and HALLER, 1964)

$$v(\hat{R}) = \hat{R}^2\left\{\frac{v(\hat{\bar{X}})}{\hat{\bar{X}}^2} + \frac{v(\hat{\bar{Y}})}{\hat{\bar{Y}}^2} - 2\frac{s_{YX}}{n\hat{\bar{X}}\hat{\bar{Y}}}\right\} \tag{28}$$

where

$$\hat{\bar{Y}} = \sum_{i=1}^{n} \frac{Y_i}{n}$$

$$\hat{Y} = \sum_{i=1}^{n} Y_i$$

$$\hat{\bar{X}} = \sum_{i=1}^{n} \frac{X_i}{n}$$

$$\hat{X} = \sum_{i=1}^{n} X_i$$

s_{YX} = covariance term

n = Number of terrestrial sample plots
(See also pp. 79–87, KÖHL 1994.)

In the NFI2, area-based inferences are consistently derived through combined ratio estimators (pp. 165, COCHRAN 1977; pp. 84, KÖHL 1994). Means of ratios are not computed, since they are biased even when large sample sizes are taken (COCHRAN 1977; SUKHATME *et al.* 1984). For inference in an area-based frame, a combined ratio estimator is used within the NFI. The ratio estimator, $\hat{R}_{ds}$, and its variance, $v(\hat{R}_{ds})$ in a double phase sampling design is calculated according to:

$$\hat{R}_{ds} = \frac{\hat{Y}_{ds}}{\hat{X}_{ds}} = \frac{\hat{\bar{Y}}_{ds}}{\hat{\bar{X}}_{ds}} \tag{29}$$

$$v\left(\hat{R}_{ds}\right) = \hat{R}_{ds}^2 \left\{ \frac{v\left(\hat{\bar{X}}_{ds}\right)}{\hat{\bar{X}}_{ds}^2} + \frac{v\left(\hat{\bar{Y}}_{ds}\right)}{\hat{\bar{Y}}_{ds}^2} - 2\frac{s_{YXds}}{n \cdot \hat{\bar{X}}_{ds} \cdot \hat{\bar{Y}}_{ds}} \right\} \tag{30}$$

$\hat{X}_{ds}, \hat{\bar{X}}_{ds}, v(\hat{\bar{X}}_{ds})$ are computed analogous to $\hat{Y}_{ds}, \hat{\bar{Y}}_{ds}, v(\hat{\bar{Y}}_{ds})$ (equation 21–23), the covariance term s_{YXds} according to.

$$s_{YXds} = \left[\frac{1}{n'^2 - n'} \sum_{h=1}^{L} \left\{ \left(n_h'^2 - n_h' \right) s_{YXh} + n_h' \hat{\bar{Y}}_h \hat{\bar{X}}_h \right\} \right] - \left[\frac{1}{n' - 1} \hat{\bar{Y}}_{ds} \hat{\bar{X}}_{ds} \right]$$

where

$$s_{YXh} = \frac{\sum_{i=1}^{n_h} (Y_{hi} - \hat{\bar{Y}}_h)(X_{hi} - \hat{\bar{X}}_h)}{n_h - 1}$$

2.1.4.5 Assigning Area Related Information to Sample Points

Assigning area and stand data to sample plots can be done either by a point decision or by an area decision. For a *point decision,* the position of the sample plot center plays a prominent role in relating area or stand related attributes to sample plots. If one sample plot covers more than one class of an attribute, the attribute class in which the sample plot center is located is assigned to the sample plot, and is independent of the actual situation. Thus, an implausible situation could result from this. Another example of this can be seen in a sample plot that is covered partially by both young and mature growth forest, and assigned to the category of young growth forest if the sample plot center falls into the young growth forest area. Because trees in a young growth forest cannot come up to the calipering limit of 12 cm, the volume of the standing timber should be zero. In the example above, it is possible that individual trees of the mature forest result in a sizeable volume which, with a point decision, is ascribed to the young growth forest. This procedure blurs the traditional forestry definition, but does not provide any difficulties for the interpretation of the results, as long as the assignment criteria are taken into consideration. In the first NFI, the stand and area related data are assigned to the individual sample plots by means of a point decision. The results of the analysis, according to stand and area related data, were never criticized (BRÄNDLI, oral communication).

In the *area decision,* the sample plot area is subdivided into different area parcels. The total of these parcels adds up to the number of area and stand categories, which can be found on the sample plots. It then follows that sample plots on stand borders are treated as two or more virtual sample plots. Each of these virtual sample plots counts as an observation and is entered separately in the database. The advantage of this procedure is that stand and area data can clearly be attributed to individual trees. The disadvantage, nowever, is the necessity to measure accurately the stand borders. The measurement is time consuming – in the NFI about thirty percent of the sample plots have forest or stand borders – and is not free from subjective influences when the borderline is defined. For successive inventories, the problem of the permanence of stand borders arises.

The assignment of stand and area related data is carried out in the second NFI analogous to the first NFI by means of point decision. The influences on the results are small and previous experience shows they are tolerated without any problems. Furthermore, the time consuming measurements of the stand borders can be dropped.

2.1.4.6 Derivation of Results for the Production Regions and Switzerland

During the derivation of the results, the characteristics which were measured on individual trees or sample plots, should be summarized in the NFI in such a way that the results are shown for units of reference that are unmistakably defined with respect to the spatial and thematic aspects.

The smallest units of reference for which the NFI provides results are the five production regions: Jura, Plateau, Pre-Alps, Alps and Southern Alps. Within these units of reference it is possible to construct thematic units with the help of variables that can be used to form classes such as tree species, stage of development, or type of ownership. In the following, spatial units are referred to as units used to report management results – in short unit of reference, while thematic units are called assessment units. The algorithm shown above can be used for either the estimator derivation of the units of reference or of the assessment units.

For data analyses, the five production regions are treated as independent populations. Therefore, from a statistical point of view, Switzerland is not covered by just one sample survey, but by five independent surveys. The results for the unit of reference “Switzerland” are derived by summarizing the results from the five production regions; that is through combining the independent surveys of the five production regions. The advantage of this procedure is that both the total values and their variances are additive. Results for the whole of Switzerland are calculated by summarizing the estimates of the five production regions. As thematically related units of reference are usually given in table form, the summaries were done independently for each table cell (=unit of reference). The following further illustrates the calculation of table values, the different types of tables, and the summaries of tables for the derivation of the results for the unit of reference “Switzerland”.

The derivation of estimates in tables is achieved independently for individual cells, the row and column margins, as well as the total sum of the table and is performed with identical algorithms. For the analysis, it is important to note that each cell can be subdivided in h strata and that the estimates for $\hat{\hat{Y}}$, $v(\hat{\hat{Y}})$, $\hat{X}$ and $v(\hat{X})$ are derived by the equations of the double sampling for stratification design. From this the analysis for the hierarchy presented in Figure 2 follows.

The number of aerial photo samples n', as well as the number of terrestrial samples n, are given by the sampling design and are constant for all cells. The number of aerial photo samples in the individual strata n_h', as well as the values of the attribute Y_i, are random variables and have to be taken into account for variance calculations. The random variable Y_i takes on the value zero in the case that the terrestrial sampling plot is not in the considered unit of reference. The consequence for calculating the cell values is that the strata weight n_h'/n' and the number of terrestrial observations n and n_h are the same for each cell. This is independent of the subunit (i.e., row and column combination), which should be analyzed. For the calculation of the total values (equation 23 to 26), A is substituted by the area of the production region. Since the stratification of the entire country was partitioned into forest and non-forest, A is the sum of all forest and non-forest areas in the production regions.

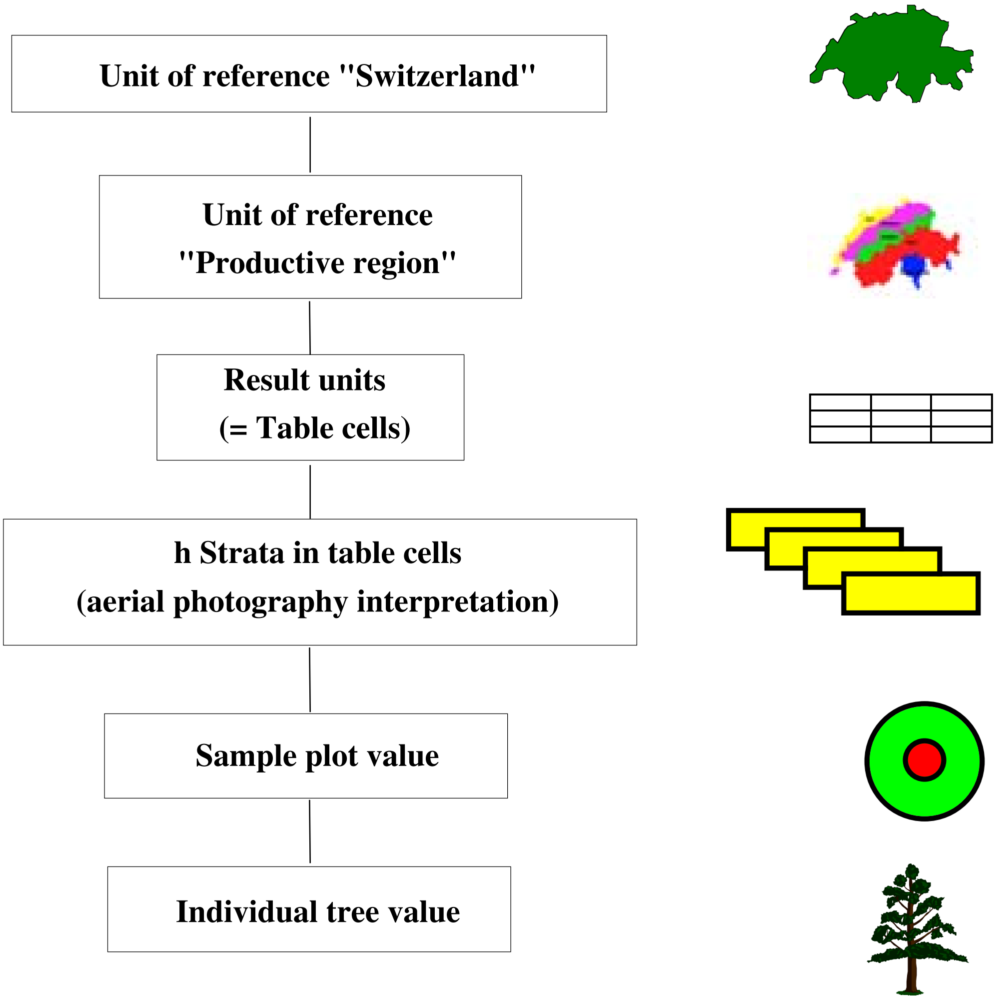

Figure 2. Hierarchy during the data analysis.

For the analysis, three types of tables have to be differentiated: attribute tables, reference tables, and ratio tables (Figure 3). These tables are similar in their structure (i.e., they represent the same thematic units in the rows and columns). In the attribute table the estimates of the attributes from the sample plots are combined. This can include measurable variables such as number of trees, basal area, standing timber, or the increment. It can be comprised of area-based measures as stand type, stage of development, or types of ownership. For area-based attributes, the area that is taken up by the sample plot of the corresponding category has to be estimated. The estimates that are derived for the individual attributes for each cell are the total $\hat{Y}$ and the variance of the total $v(\hat{Y})$.

The reference tables are also the denominators of the ratio estimator. They can, for example, encompass an area of area-based attributes such as the number of trees per hectare, the number of trees for the number of tree proportions, or the basal area for the basal area proportion. In the following, the attention is mainly drawn to the area tables as reference tables, since these are by far the most frequently used applications in the NFI.

Within the area tables, the total area $\hat{X}$ and its variance $v(\hat{X})$ are presented for each table cell. With the help of the area tables, it is possible to transform the attribute tables into ratio tables (i.e., tables with a unit area). The area tables only have to be derived once for all subunits (cells) and can then be employed for all attribute tables with the same row and column categories. The estimates of the cells in the ratio tables are taken from the ratio $\hat{R}$, which is formed by taking the ratio of the sum of the attribute $\hat{Y}$ and the sum of the area $\hat{X}$. For the calculation of the variance for the ratio, the variance of the individual cell $v(\hat{Y})$ and $v(\hat{X})$, as well as the covariances, are used.

For the derivation of area tables, it is important to pay attention to which area definition should be used in the analysis. For example, the area-related standing timber volume of spruce can be calculated either for the entire region, the forested area, or for the area with spruce forest.

Up to this point, the analysis of the five production regions has been described. For each of the production regions in their thematic subdivisions, identical attributes, areas and ratio tables are calculated. For the derivation of the results for the unit of reference “Switzerland”, these tables must be combined.

The total of an attribute for the unit of reference “Switzerland” is calculated by summing up the totals of the tables.

$$\hat{Y}_{CH} = \sum_{k=1}^{5} \hat{Y}_k \tag{31}$$

$$\hat{X}_{CH} = \sum_{k=1}^{5} \hat{X}_k \tag{32}$$

Since this is the sum of five random variables, the variance of the totals can be calculated according to:

$$v\left(\hat{Y}_{CH}\right) = \sum_{k=1}^{5} v\left(\hat{Y}_k\right) = \sum_{k=1}^{5} A_k^2 v\left(\hat{\bar{Y}}_k\right) \tag{33}$$

$$v\left(\hat{X}_{CH}\right) = \sum_{k=1}^{5} v\left(\hat{X}_k\right) = \sum_{k=1}^{5} A_k^2 v\left(\hat{\bar{X}}_k\right) \tag{34}$$

Results related to unit area are derived analogously to the procedure in the individual production regions (equation 27 and 28), by utilizing the tables, which are obtained through summation for the unit of reference Switzerland.

$$\hat{R}_{CH} = \frac{\hat{Y}_{CH}}{\hat{X}_{CH}} \tag{35}$$

$$v(\hat{R}_{CH}) = \frac{v(\hat{Y}_{CH}) + \hat{R}^2_{CH} v(\hat{X}_{CH}) - 2\hat{R}_{CH} s_{YXCH} / n}{\hat{X}^2_{CH}} \tag{36}$$

where

$$s_{YXCH} = \sum_{k=1}^{5} A_k^2 s_{YXk} \tag{37}$$

These estimates are derived for the individual cells. Thus, for each cell of the ratio table of the unit of reference "Switzerland", five estimators are applied: $\hat{Y}_k, \hat{X}_k, v(\hat{Y}_k), v(\hat{X}_k)$, and s_{YXk}. Since the tables are additive, the estimates for the individual cells do not have to be adjusted. Therefore, table totals for an individual attribute presented in several tables with different thematic units of reference (i.e., column and row headers) are identical.

Attribute table
Total ($\hat{Y}$)

$\hat{Y}_{11}$	$\hat{Y}_{21}$	$\hat{Y}_{31}$
$\hat{Y}_{12}$	$\hat{Y}_{22}$	$\hat{Y}_{32}$
$\hat{Y}_{13}$	$\hat{Y}_{23}$	$\hat{Y}_{33}$

V [m^3]

$\hat{Y}_{11}$	$\hat{Y}_{21}$	$\hat{Y}_{31}$
$\hat{Y}_{12}$	$\hat{Y}_{22}$	$\hat{Y}_{32}$
$\hat{Y}_{13}$	$\hat{Y}_{23}$	$\hat{Y}_{33}$

G [m^2]

$\hat{Y}_{11}$	$\hat{Y}_{21}$	$\hat{Y}_{31}$
$\hat{Y}_{12}$	$\hat{Y}_{22}$	$\hat{Y}_{32}$
$\hat{Y}_{13}$	$\hat{Y}_{23}$	$\hat{Y}_{33}$

N [n]

$\hat{Y}_{11}$	$\hat{Y}_{21}$	$\hat{Y}_{31}$
$\hat{Y}_{12}$	$\hat{Y}_{22}$	$\hat{Y}_{32}$
$\hat{Y}_{13}$	$\hat{Y}_{23}$	$\hat{Y}_{33}$

I [m^3]

$\hat{Y}_{11}$	$\hat{Y}_{21}$	$\hat{Y}_{31}$
$\hat{Y}_{12}$	$\hat{Y}_{22}$	$\hat{Y}_{32}$
$\hat{Y}_{13}$	$\hat{Y}_{23}$	$\hat{Y}_{33}$

Young growth [ha]

$\hat{Y}_{11}$	$\hat{Y}_{21}$	$\hat{Y}_{31}$
$\hat{Y}_{12}$	$\hat{Y}_{22}$	$\hat{Y}_{32}$
$\hat{Y}_{13}$	$\hat{Y}_{23}$	$\hat{Y}_{33}$

Pole wood [ha]

Reference table
Area ($\hat{X}$)

$\hat{X}_{11}$	$\hat{X}_{21}$	$\hat{X}_{31}$
$\hat{X}_{12}$	$\hat{X}_{22}$	$\hat{X}_{32}$
$\hat{X}_{13}$	$\hat{X}_{23}$	$\hat{X}_{33}$

[ha]

Ratio table
Area base ($\hat{R}$)

$\hat{R}_{11}$	$\hat{R}_{21}$	$\hat{R}_{31}$
$\hat{R}_{12}$	$\hat{R}_{22}$	$\hat{R}_{32}$
$\hat{R}_{13}$	$\hat{R}_{23}$	$\hat{R}_{33}$

V [m^3/ha]

$\hat{R}_{11}$	$\hat{R}_{21}$	$\hat{R}_{31}$
$\hat{R}_{12}$	$\hat{R}_{22}$	$\hat{R}_{32}$
$\hat{R}_{13}$	$\hat{R}_{23}$	$\hat{R}_{33}$

G [m^2/ha]

$\hat{R}_{11}$	$\hat{R}_{21}$	$\hat{R}_{31}$
$\hat{R}_{12}$	$\hat{R}_{22}$	$\hat{R}_{32}$
$\hat{R}_{13}$	$\hat{R}_{23}$	$\hat{R}_{33}$

N [n/ha]

$\hat{R}_{11}$	$\hat{R}_{21}$	$\hat{R}_{31}$
$\hat{R}_{12}$	$\hat{R}_{22}$	$\hat{R}_{32}$
$\hat{R}_{13}$	$\hat{R}_{23}$	$\hat{R}_{33}$

I [m^3/ha]

$\hat{R}_{11}$	$\hat{R}_{21}$	$\hat{R}_{31}$
$\hat{R}_{12}$	$\hat{R}_{22}$	$\hat{R}_{32}$
$\hat{R}_{13}$	$\hat{R}_{23}$	$\hat{R}_{33}$

Young growth [proportion]

$\hat{R}_{11}$	$\hat{R}_{21}$	$\hat{R}_{31}$
$\hat{R}_{12}$	$\hat{R}_{22}$	$\hat{R}_{32}$
$\hat{R}_{13}$	$\hat{R}_{23}$	$\hat{R}_{33}$

Pole wood [proportion]

Figure 3. Types of tables[1].

---

[1] The thematic units of the rows and columns are for all tables identical. Columns could, for example, represent a subdivision in "private forest," "public forest," and "total;" rows could represent a partition into "conifers," "broadleaf," and "total." For such a partition, the total of the reference unit would be written in the lower right cell (index 33).

2.1.4.7 Estimation of Current Values and Change

Apart from recording the current values of forests, the second NFI serves as the first remeasurement as a way to assess change. The statistical approaches shown above are derived primarily to estimate current values. They can also be applied to estimate change provided that two conventions are introduced for analysis.

The first convention is concerned with the change that is observed on individual trees or is derived from data collected from individual trees. Standing timber falls into this category. If each individual tree is associated with some attributes which quantify the change between the first and the second survey, the change can be analyzed just as current values. For the volume increment, each individual tree is assigned an attribute that represents the change between NFI1 and NFI2. The increment is derived similarly to the individual tree volume via functions (see Chapter 2.1). By doing so, changes can be treated as individual tree attributes.

The second convention is concerned with the number of sample plots that are used to estimate the current values and change. As described above, SPR does not result in additive tables. This is the main reason to drop the SPR estimators in favor of the CFI estimators, and to choose two different sample sizes to estimate current values and change. For estimating change, only permanent sample plots were used; that is only those plots which were included in the first as well as the second inventory. The respective sample sizes are compiled in Table 1.

Table 1. Sample size in NFI2.

	Estimation of Current Values	Estimation of Change
Aerial Photo samples	165'190	40'000
Permanent samples[1]	23'227	23'227
Temporary samples[1]	2'400	–

[1] Forest and Non-Forest Samples

A departure from this concept affects the estimation of those attributes where change is derived from a model. In this case, change can also be reported for temporary sample plots so that the sample size for estimating change is accordingly higher. In essence, this affects the estimation of increment that is described in Chapter 3.2.

2.1.5 Optimization

The goal of the inventory planning is the development of an “optimal” sampling design, which allows for a given budget to estimate the desired characteristics with a sampling error as small as possible. Apart from the cost, which is the strongest constraint, the inventory planning must consider the tolerable range of error, the characteristic of the forest to be surveyed, the available personnel, and the geographic or thematic units of reference.

During the planning of the second NFI it did not suddenly happen that one inventory design was the only suitable method. Instead, several possible methods were developed. Based on objective decision rules, the procedure that was best suited for the goal of the second NFI was chosen. Because the development of each sampling design variation is a time consuming process, the mistake of committing very early to only one single design is made for many inventories in the preparation phase. After that phase, it is often not clear why a certain design was chosen, and the choice of one method over another is not solely justified by the optimization objective alone.

The goal of the sample design optimization is to increase cost efficiency. The cost efficiency is described as the relative efficiency between two design alternatives. The relative efficiency of design A versus design B at a given cost is the ratio of the variance of both alternatives $\frac{\sigma_B^2}{\sigma_A^2}$ (p.

103, COCHRAN 1977). Therefore, it is necessary to obtain information about the cost as well as the variances in order to be able to compare both design alternatives.

In the comparisons between the sampling design variations, only such costs should be considered which vary with the sample size. Fixed costs, which are the same for all variations and do not change the sample size, should be excluded (WÖHE 1981). A general cost function for the double sampling design for stratification at both inventory occasions is:

$$C = C_p n' + C_{12} n_{12} + C_{-2} n_{-2}$$

where

C = Total variable costs.
C_p = Costs for the interpretation of one aerial photo sample plot.
C_{12} = Costs for the survey of one permanent, terrestrial sample plot.
C_{-2} = Costs for the survey of one new (temporary), terrestrial sample plot.
n' = Number of aerial photo sampling units.
n_{12} = Number of permanent sample plots
n_{-2} = Number of temporary sample plots

For each alternative there exists an optimal combination of sample sizes. This combination must be compared against the other alternatives. The optimum can be determined in two different ways:

- Minimizing cost for a predetermined precision
- Minimizing the errors for given cost

The above problem is a standard form of an optimization problem: The minimization of a target function under certain defined constraints. COCHRAN (1977) presents solutions for double sampling for stratification. WARE and CUNIA (1962) show SPR solutions for two different occasions. BICKFORD *et al.* (1963) derive solutions for double sampling for stratification combined with SPR for two different occasions.

In complex cases, numerical methods have to be applied. The classical method is the linear programming method, where the target function with linear equality and inequality conditions is linear (HILLIER and LIEBERMAN 1974). This method is limited in its application, since for many optimization problems either the target function or the conditions are not linear, or solutions with integer values are required.

SCOTT and KÖHL (1993) discussed the application of the m-neighborhood-method (GARFINKEL and NEMHAUSER 1972), an integer non-linear programming method, in the context of forest inventories. With this method, all possible combinations of m starting points above and below some initial sample sizes of each variable are tested for the combination that minimizes the optimization function the most. The predetermined settings are varied until no further improvements can be achieved. The m-neighborhood-method does not guarantee that the global optimum can be found. Nevertheless, it ensures an improvement over the preset starting point.

During the preparation of the second NFI, SCOTT and KÖHL (1993) developed a special program (SIZE) for the optimization of sampling procedures. The procedure is based on the m-neighborhood-method and makes it possible to derive the optimal sample size for three different sampling methods (simple random sampling, stratified sampling, and double sampling for stratification) with one, two or three different successive inventories. SPR as well as CFI estimators can be compared. The program requires some details about the population, the cost coefficients, and about the variability of the variables of interest. This approach also allows, apart from the simple comparison of different design alternatives, a sensitivity analysis to be conducted. By varying the input parameters it is possible to investigate the consequences in respect to cost efficiency. With this, it is possible to find design alternatives which represent an optimal solution only under the most restricted circumstances. For inventory purposes, solutions should be preferred that are robust against changes in the input parameters over a wide range, so that they do not differ too much in respect to the optimal solution but are still cost efficient.

In contrast to aerial photography interpretation, the cost for the field survey is not constant over the entire country of Switzerland. It differs depending on the accessibility and topography, and for permanent and temporary sample plots as well.

For the optimization of the NFI, several different sampling designs were investigated. As examples, three different alternatives are presented:

a) One-phase sampling design:
   This procedure does not include stratification based on aerial photographs and corresponds with the statistical design of the first NFI. The variables of interest are measured on terrestrial sample plots. Aerial photography is exclusively used to determine forested area and forest area proportions.
b) Double sampling for stratification (DSS) design with permanent samples:
   Here, aerial photo samples are used to estimate the strata size, and the permanent sample plots from the first NFI are used. If more than six million Swiss Francs (CHF) would be available for the field survey and the interpretation of aerial photographs, additional new (temporary) sample plots should be included.
c) Double sampling for stratification design with permanent and new samples:
   The number of new sample plots is given first. Starting at a certain cost threshold it is possible to raise the number of permanent sample plots similar to alternative b, until the total expenses are reached.

In Figures 4 and 5, the standard errors in percent for the estimation of the standing volume (Figure 4) and the estimation of the number of trees (Figure 5) are plotted against the cost for the three sampling design alternatives. For the same cost, the standard error is smaller for the standing timber than for the number of trees. Nevertheless, the trend of the curves is similar for both features. The curves for all double sampling design alternatives merge for expenses costing more than six million CHF. The reason for this is that with these expenses not only all 11,000 permanent samples of the first NFI are measured, but new sample plots are included as well.

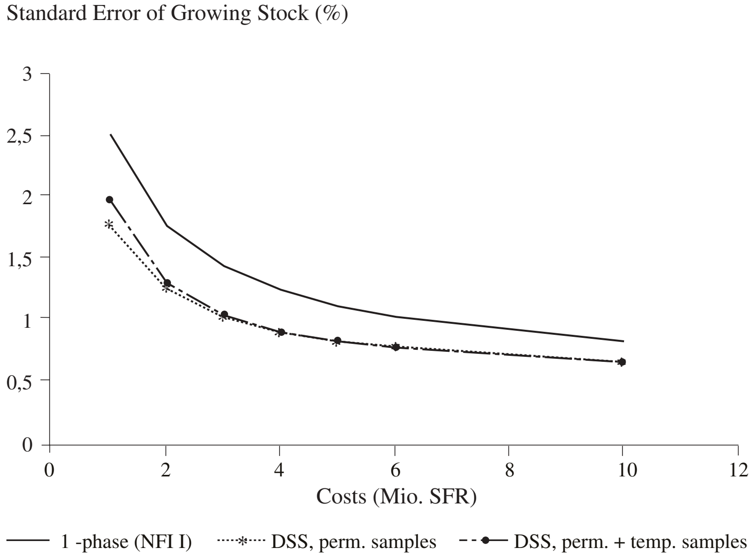

Figure 4. Standard error of the timber volume.

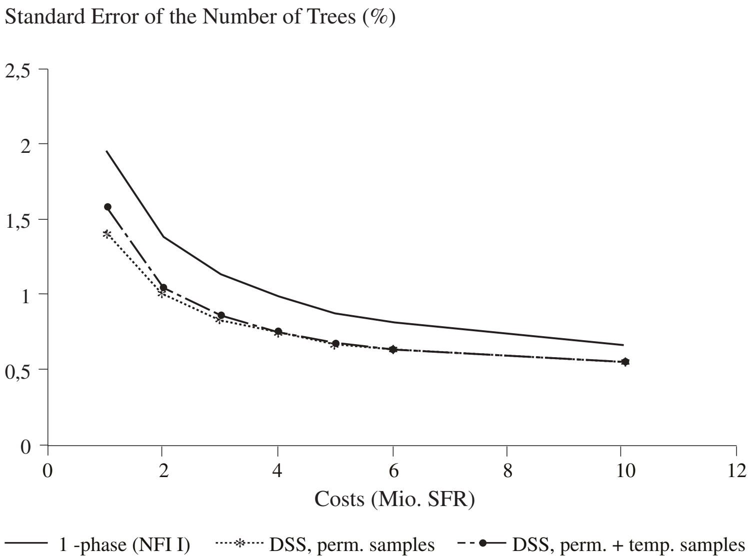

Figure 5. Standard error of the stem number.

With the one-phase sampling design (alternative a), a relatively high standard error results. The double sampling designs are, in all situations, more cost efficient. The survey of a permanent sample plot is less expensive than establishing a new sample plot. Therefore, it is possible to survey a larger number of sample plots with alternative b (DSS, permanent samples) at the same cost than for alternative c. For the estimation of current state, only measurements from the second occasion are applied. The values of the first occasions have not been updated. For this reason, the number of surveyed forest sample plots at the second occasion directly affects the size of the standard error and, therefore, alternative b is more cost efficient for expenses less than six million CHF.

Another important aspect of the sampling design planning is apparent in Figures 4 and 5. Higher expenses do not result in a constant reduction of the standard error. Increasing the budget at lower expenses results in a large reduction of standard errors, while the curve for the standard errors flattens with increasing expenses. This means increasing the budget when it is already at a high level results in a smaller reduction of the sampling error. For the second NFI, about three million CHF were available for the variable cost, which is approximately the range in which the cost efficiency is at its optimum. Increasing the budget would by far influence the standard errors less than cutting the budget. For expenses over four million CHF, it is questionable whether the financial resources can effectively be used. Instead of increasing the number of forest sample plots, it seems more reasonable to measure additional characteristics such as data for vegetation, soil, or non-wood goods and services.

The decision for a specific alternative for the second NFI was made in favor of the double sampling design. In addition to the survey of the forest sample plots, aerial photo plots were interpreted in order to estimate strata sizes. The double sampling alternative without new samples was more cost efficient in respect to the estimation of current values. However, the difference in cost efficiency with the available funds was very small. Since new samples allowed the sample plots to be investigated with respect to their representativeness, new terrestrial samples were measured for the second NFI, even though this meant a slight decrease in cost efficiency.

The optimization for the given budget led to surveys in three different grids:

- Aerial photo interpretation in a 500 x 500 meter grid with 165,190 aerial photo samples.
- Survey of permanent samples in a 1.4 x 1.4 km grid with 23,227 forest and non-forest samples (5513 of them permanent forest sample plots).
- Survey of new samples on a subsample of the 500 x 500 meter grid with 2,400 new (temporary) forest and non-forest samples, where approximately 670 of them were forest samples.

2.1.6 Discussion

The demands on the possible analysis of the second NFI were determined by the published results of the first NFI (EAFV 1988). Additionally, the second NFI had to provide information about changes. The attributes used in the NFI can be divided into two groups: qualitative variables and quantitative variables. Both variable groups can be analyzed with the previously introduced method of ratio estimation. However, the qualitative variables are treated as ratio estimates.

For the calculation of statistical parameters related to unit area by ratio estimators, attribute data and area data must be linked. The calculation of standard errors of a ratio requires the derivation of the variance of the attribute of interest, the variance of the respective area, and the covariance. Total values and means based on measurements of the sample plots have to be independently derived.

The analysis of the inventory data can be interpreted as associating tables with each other. On the one hand, there are tables of attributes and, on the other hand, there are tables of area data. The table cells are determined by several different categorical variables. In the table cells, records of total values, means and variances can be found. For calculating tables which present results in unit area (e.g. volume in m^3/ha), the same area table can be utilized for several attributes, as long as the thematic separation of rows and columns (i.e., the units of reference represented by each table cell) are the same. For calculation of the standard errors, it is only necessary to derive the covariance in addition to the variances. This approach reduces the required calculations to a minimum while, at the same time, ensuring the flexibility of the analysis system. It is possible to use only a few standard modules (e.g. the variance or covariance calculation), and allows for extensive use of standard software. In addition, the analysis concept can be integrated into a databank concept – an aspect which SCOTT (1986) doubted was possible for the application of SPR. The integration of standard software also reduced the efforts needed to validate the software system prepared for the analysis, as well as the required time for the programming.

By using CFI estimators, the problem of non-additive tables can be avoided. The analysis can therefore be carried out for any unit of reference without having problems with the compatibility of the results with other units of reference. The grand total of tables with different row and column settings will agree without any additional adjustments.

2.1.7 Literature

BICKFORD, C.A. 1956. Proposed Design for Continuous Forest Inventory: a System Perpetual Forest Survey for the Northeast. In: *USDA Forest Service* (Editor): Eastern Technical Meeting, Forest Survey, Oct. 8–12, in Cumberland Falls, KY.

BICKFORD, C.A. 1959: A Test of Continuous Inventory for National Forest Management Based upon Aerial Photographs, Double Sampling and Remeasured Plots. Proc. Society of American Foresters:143–148.

BICKFORD, C.A.; MAYER, C.F.; WARE, K.D. 1963: An Efficient Sampling Design for Forest Inventory: The Northeastern Forest Survey. J. For. 61:826–833.

BIOLLEY, H.E. 1921. L`aménagement des forêts par la méthode expérimentale et spécialment la méthode du contrôle. Paris, Neuchatel. 90 p.

BOWDEN, D.C.; DIXON, G.E.; FRAYER, W.E.; GRAYBILL, F.A.; JEYARATNAM, S.; JOHNSTON, D.C.; KENT, B.M.; LABAU, V.J.; ROBERTS, E. 1979. Multi-Level Sampling Designs for Resource Inventories. Ft. Collins, CO: Dept. of Forest and Wood Sciences, Colorado State University, Rocky Mountain Forest and Range Exp. Station, USDA Forest Service.

COCHRAN, W.G. 1977. Sampling Techniques. New York: J. Wiley & Sons. 428 p.

EAFV (Eidg. Anstalt für das forstliche Versuchswesen); BFL (Bundesamt für Forstwesen und Landschaftsschutz). 1988. Schweizerisches Landesforstinventar. Ergebnisse der Erstaufnahme 1982–1986. Ber. Eidgenöss. Forsch.anst. Wald Schnee Landsch. 305: 375 p.

GARFINKEL, R.S.; NEMHAUSER, G.L. 1972. Integer Programming. New York: John Wiley & Sons. 427 p.

GRAVES, H.S. 1906. Forest Mensuration. New York: John Wiley & Sons. 458 p.

GURNAUD, A. 1878. Cahier l`aménagement pour l`application de la méthode par contenance exposée sur la forêt des Eperous. Paris. 160 p.

HILDEBRANDT, G. 1961: Methoden der Waldinventur im Nordwesten und in den Rocky Mountains der USA. Allg. Forstz. 16 (1).

HILDEBRANDT, G. 1962: Luftbildauswertung bei Waldinventuren im Gebiet der Sommer- und Nadelwälder. Allg. Forstz. 17 (1/2):20–26.

HILLIER, F.S.; LIEBERMAN, G.J. 1974. Operations Research. 2 ed. San Francisco: Holden-Day Inc. 800 p.

ITTEN, K.I.; NANAYAKKARA, S.D.F.C.; HUMBEL, R.; BICHSEL, M.; SOMMER, M. 1985. Inventory and Monitoring of Sri Lankan Forests Using Remote Sensing Techniques. In: *Schmid-Haas, P.* (Editor): Inventorying and Monitoring Endangered Forests, IUFRO Conference, August 19–24, 1985, in Zurich.

JOHNSTON, D.C. 1982. Theory and Application of Selected Multilevel Sampling Designs. PhD-Thesis, Colorado State University, Ft.Collins, Colorado.

KISH, L. 1965. Survey Sampling. New York: J. Wiley & Sons. 643 p.

KLEINN, C. 1991: Der Fehler von Flächenschätzungen mit Punkterastern und Linienförmigen Stichproben. Mitt. der Abt. Forstl. Biometrie der Universität Freiburg 91 (1):128 p.

KÖHL, M. 1991: Vierphasiges Stichprobendesign zur Holzvorratsschätzung: Ergebnisse einer Pilotinventur in Indien. In: OESTEN, G. , KUNTZ, S., GROSS, C.P. (Editor): Fernerkundung in der Forstwirtschaft. Karlsruhe: Wichmann Verlag. 170–187.

KÖHL, M. 1994: Statistisches Design für das zweite Schweizerische Landesforstinventar: Ein Folgeinventurkonzept unter Verwendung von Luftbildern und terrestrischen Aufnahmen. Mitt. Eidgenöss. Forsch.anst. Wald Schnee Landsch. 69 (1):141.

KÖHL, M.; GERTNER, G. 1992: Geostatistische Auswertungsmöglichkeiten für Waldschadeninventuren: Methodische Überlegungen zur Beschreibung räumlicher Verteilungen. Forstw. Cbl. 111:320–331.

KÖHL, M.; GREEN, E.J. 1991: Empirische Bayes-Schätzer zur Auswertung von Forstinventuren. Forstwissenschaftliches Centralblatt 110:393–399.

KRUTZSCH, H.; LÖTSCH, F. 1938. Holzvorratsinventur und Leistungsprüfung der naturgemässen Forstwirtschaft. Neudamm: Verlag Neumann. 164 p.

KUSHWAHA, S.P.S. 1990: Forest Type Mapping and Change Detection From Satellite Imagery. Journal of Photogrammetry and Remote Sensing 45:175–181.

LANGLEY, P.G. 1975. Multistage Variability Sampling: Theory and Use in Estimating Timber Resources from Space and Aircraft Photography. PhD-Thesis, University of California, Berkeley, California.

LOETSCH, F., HALLER, K.E., 1964: Forest Inventory, Vol. 1. München, BLV-Verlagsgesellschaft. 436 p.

MEIER, P. 1953: Variance of a Weighted Mean. Biometrics 9: 59–73.

PATTERSON, H.D. 1950: Sampling on Successive Occasions with Partial Replacement of Units. Jour. Royal Statis. Soc., Ser. B 12 (2):241–255.

POSO, S. 1972: A Method of Combining Photo and Field Samples in Forest Inventory. Commun. Inst. For. Fenn. 76 (1):133.

RAO, J.N.K. 1973: On Double-Sampling for Stratification and Analytical Surveys. Biometrika 60:125–133.

SCHADE, J. 1980. Ein mehrphasiges Stichprobensystem für forstliche Grossrauminventuren gestützt auf Landsat MSS Daten, Luftbilder 1:50'000 und ergänzende terrestrische Messungen. PhD-thesis, Universität Freiburg, Freiburg.

SCHMID, P. 1967: Die Weiterentwicklung der Leistungskontrolle in der Schweiz. Wiss. Zeitschrift d. techn. Univ. Dresden 16 (2).

SCHMID-HAAS, P. 1983: Information on Drain by Forest Inventories. In (Editor): Forest Inventories for Improved Management. Helsinki: Helsingin Yliopiston Metsänarvioimistieteen Laitos, Tiedonantoja. 50–61.

SCHMID-HAAS, P.; WERNER, J.; BAUMANN, E. 1993: Kontrollstichproben: Aufnahmeinstruktion (3. überarbeitete Auflage). Ber. Eidgenöss. Forsch.anst. Wald Schnee Landsch. 186:143.

SCOTT, C.T. 1981: Simplified Estimators for Sampling with Partial Replacement on Multiple Occasions. Staff Paper 23:48.

SCOTT, C.T. 1984: A New Look at Sampling with Partial Replacement. Forest Sci. 30:157–166.

SCOTT, C.T. 1986: An Evaluation of Sampling with Partial Replacement. In: Soc. American Foresters (Editor): Use of Auxiliary Information in Natural Resource Inventories. SAF Publication. 74–79.

SCOTT, C.T.; KÖHL, M. 1993: A Method for Comparing Sampling Design Alternatives for Extensive Inventories. Mitt. Eidgenöss. Forsch.anst. Wald Schnee Landsch. 68 (1):62.

SCOTT, C.T.; KÖHL, M. 1994: Sampling with Partial Replacement and Stratification. Forest Science 40 (1):30–46.

STIERLIN, H.R.; BRÄNDLI, U.B.; HEROLD, A.; ZINGGELER, J. 1994. Schweizerisches Landesforstinventar: Anleitung für die Feldaufnahmen der Erhebung 1993–1995. Birmensdorf: Eidgenöss. Forsch.anst. Wald Schnee Landsch.

STOTT, C.B.; RYAN, E.J. 1939: A Permanent Sample Technique Adapted to Commercial Timber Stands. J. For. 37:347–349.

STOTT, C.B.; SEMMES, G. 1962. Our Changing Inventory Methods and the CFI System in North America. In: 5th World Forest Congress, in Seattle.

SUKHATME, P.V.; SUKHATME, B.V.; SUKHATME, S.; ASOK, C. 1984. Sampling Theory of Surveys with Applications. Ames, Iowa: Iowa State University Press. 526 p.

TRACHSLER, H.; KÖLBL, O.; MEYER, B.; MAHRER, F. 1980. Stichprobenweise Auswertung von Luftaufnahmen für die Erneuerung der Arealstatistik. Bern: Bundesamt für Statistik und Bundesamt für Raumplanung. 98 p.

UNNI, M.V.M. 1990. Space and Forest Management. In: *Rao, U.R.* (Editor): 41st IAF Congress, October 6–13, 1990, Dresden.

WARE, K.D. 1960. Optimum Regression Sampling Design for Sampling of Forest Populations on Successive Occasions. Unpublished Ph. D. Dissertation, Yale University.

WARE, K.D.; CUNIA, T. 1962: Continuous Forest Inventory with Partial Replacement of Samples. For. Sci. Monograph 3:40 p.

WÖHE, G. 1981. Einführung in die allgemeine Betriebswirtschaftslehre. München: Vahlen. 1245 p.