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SAMPLING METHODS FOR ESTIMATING CHANGE IN FOREST RESOURCES

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Abstract. Changes in forest resources have been estimated in a variety of ways. This paper focuses on extensive forest surveys rather than on sentinel-site investigations. The sampling design and plot design used are key to precise estimates of change. Alternative sampling designs include temporary surveys, Continuous Forest Inventory, and Sampling with Partial Replacement. Each can be used in conjunction with stratified sampling or double sampling for stratification. Plot designs can involve variable-radius or Bitterlich sampling for trees, and fixed-area plots for most attributes. In extensive surveys, it is efficient to group plots into clusters. Plots must be sampled at a frequency that is commensurate with the rate of change, degree of interest, and funding available. Often, plots are less than a hectare in size and spaced widely across the population. Continuous Forest Inventory, with or without stratification, is efficient for estimating current values, net change, and components of change. Much work remains in scaling to understand landscape-level interactions and to identify stressors and indicators of forest health and sustainability.

Key words: change estimation; Continuous Forest Inventory; forest sampling; monitoring; plot design; sampling with partial replacement; systematic sampling.

INTRODUCTION

Forestry has a long tradition of monitoring forest resources to ensure their sustainable use. In Europe, plots were established in the late 1800s. In the United States, the USDA Forest Service began conducting surveys in the 1930s. Initially, the surveys focused on current resources, particularly volume by tree species. Due to the efforts of Stott (1947) and others, the focus began to shift to estimates of change in the late 1950s. Since then, many methods of conducting forest surveys have been explored to meet a variety of objectives.

This paper presents forest sampling and estimation methods that have been used in monitoring change in forest resources, primarily in the U.S. There are many aspects of monitoring for the estimation of change. The sampling design determines the method of selecting sample locations. The plot design determines the size, shape, number, and spatial arrangement of plots at each sample location. Scale issues include the sampling frequency and the spatial scale at which the ecosystem processes of interest must be observed. Each of these must be taken into account in determining efficient analytical methods. Finally, the choice of the attributes is key to monitoring, because the attributes chosen must answer questions raised when monitoring objectives are set.

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SAMPLING DESIGNS

Forest sampling has drawn heavily on general sampling methods and agricultural methods, but it also has some methods that are unique to forestry, such as using a prism to sample trees in proportion to their cross-sectional area. But selecting the sampling design is just one of many steps involved in forest monitoring.

I recommend that any forest monitoring design use permanent plots to estimate change. This requires monumenting plot locations with such things as Global Positioning System coordinates, pinpricks on aerial photographs, sketch maps, written directions, witness trees, distances and directions from known points to the plot centers, and center stakes. For forest surveys, this also requires recording the coordinates of each tree, typically by recording the distance and direction from plot center to each tree. In this way, each plot and each tree can be revisited to observe the change since the previous survey and determine the status of individual trees with respect to ingrowth, accretion, mortality, or harvest.

Alternative designs for sampling over time

Sampling is used to make inferences about a population of interest that is too large or too expensive to measure completely. Sampling designs are ways of selecting parts of the population for measurement. In forest resource surveys, the sample locations almost always are based on sample locations (a map), rather than choosing individual organisms (a list). Thus, forest monitoring and estimation usually are area based rather than individual–organism based. This has implications for the estimation procedures that are discussed later.

Historically, extensive forest surveys for change estimation have taken three forms. The first is a series of temporary, independent surveys that are efficient for estimating current values. Change is estimated as the difference between the current and previous estimates. The variance of the change is estimated as the sum of the variance of the current and previous values. Such change estimators are inefficient (Schreuder et al. 1993).

In the second form, Continuous Forest Inventory (CFI) or permanent-plot surveys (Stott 1947), all plots established at the first survey (occasion) are remeasured at all subsequent occasions. The disadvantage of this method is that estimation depends on a representative (characteristic) sample being taken at the first occasion. The method tends to reduce the impact of an unrepresentative sample with each succeeding and different sample. The primary advantage of CFI over temporary surveys is that the variance of change estimates are reduced by the positive covariance between the occasions (much like a paired t test). In practice, if the time between surveys does not exceed 15 yr, the covariance significantly reduces the variance of the change in timber volume estimates, for example. Thus, permanent-plot surveys result in precise estimates of change. In addition, permanent plots can be used to estimate the components of change, because change is directly estimated rather than indirectly, as in temporary surveys. An example is the components of net change in volume: ingrowth (new trees), accretion (growth on sample trees), mortality, and harvest. None of these components of net change can be estimated accurately from temporary surveys (e.g., Schreuder et al. 1993).

The third form is Sampling with Partial Replacement (SPR). Developed by Patterson (1950) and modified for forestry applications by Ware and Cunia (1962), SPR uses a combination of temporary and permanent plots. For example, at the second occasion, some of the initial plots are remeasured and some new plots are added. The temporary samples help keep the sample representative. The remeasured samples provide estimates of the components of change. Together they provide efficient estimates of current values and good estimates of change. This efficiency is a result of using the remeasured plots to develop simple linear regression equations ("new" regressed on "previous" values) to "update" the first occasion sample mean (remeasured and unremeasured). This estimate is then combined with the estimate from the new sample, making use of all available information. The number of new vs. remeasured plots can be adjusted to optimize for both current and change estimates.

SPR is a general sampling design. Both CFI and temporary surveys can be thought of as special cases of SPR. Perhaps an even more general term is rotation sampling (Duncan and Kalton 1987). As with SPR, some samples are dropped and new ones added. With SPR,

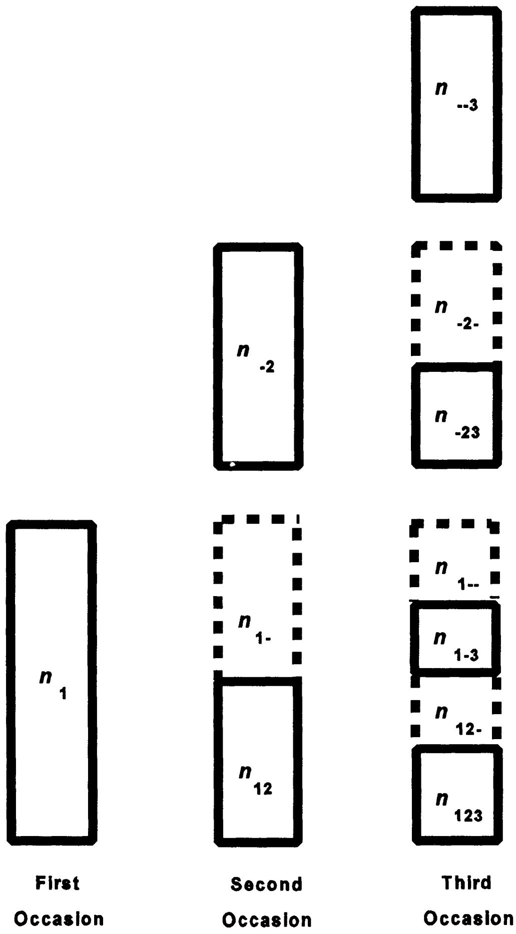

FIG. 1. Sampling with Partial Replacement on three occasions showing the different groupings of plots based on the occasions at which they are measured (solid lines) vs. updated (dashed lines). Subscripts indicate occasions measured.

some plots established at each of the previous occasions are remeasured at the current occasion, allowing the previous occasions to be updated to the present. With rotation sampling, this is not a restriction. Plots are established and remeasured one or more times. They can be dropped for one or more measurements and then returned to the sample. The estimation can be more difficult.

For example (Fig. 1), with SPR at the third occasion, the survey planner must determine the number of plots to remeasure that were remeasured at the second occasion (n_{123}), the number of plots to remeasure that were measured at the first but not the second occasion (n_{1-3}), the number of plots to remeasure that were established at the second occasion (n_{-23}), and the number of new plots to establish (n_{--3}). The remeasured plots can then be used to update the plots established at each of the two prior occasions, forming two independent estimates since they were drawn from two independent samples. These can then be combined with the estimate from the new plots using optimal weights based on their respective variances (Meier 1953). This is straightforward for current values. Net change can be computed by taking the difference between the estimates from the current and previous occasions or by enhancing previous estimates using the new plots (Scott and Köhl 1994). Either way, the estimates of the variance become complicated. Components of change can be estimated only from the remeasured plots, making it difficult to ensure that they add to the estimate of net change (Van Deusen 1989, Scott and Köhl 1994).

With SPR, planning becomes more complex due to the number of options added at each survey occasion (Scott 1986). Although the analysis is straightforward for any single estimate, many regressions must be fit for every attribute. Because regression estimators are not always well behaved, they must be monitored carefully. Plots that have been disturbed (harvested, cleared, or planted) dramatically alter the results. If stratification is used with SPR (Scott and Köhl 1994), the homogeneity within strata can break down over time. Finally, in tables estimated with SPR, the cells do not sum to the estimated table margins (Li and Schreuder 1985) both within and between occasions. Most of these comments also apply to rotation sampling.

Sample location alternatives

Each of the three alternative designs for sampling over time can be used in conjunction with several sample location alternatives or options. Two common methods of selecting samples are random selection (using simple random sampling), or on a grid (using systematic sampling). Although systematic samples are not located randomly, the simple random sampling variance estimator has been shown to have small bias and perform well (Reber and Ek 1983). Examples of finding periodicity in the observations that matches the grid are rare. Typically, the variance estimator is slightly high (conservative). For this reason and because the sample is well distributed across the population, systematic sampling is recommended over simple random sampling for forestry applications.

Another option is the use of stratification to reduce variation and thus improve the odds of detecting change. In forestry, stratification can take two forms. Stratified random sampling (Cochran 1977) is applicable when the entire population can be classified into different strata. This can be done on maps or aerial photographs, or with satellite imagery. The key is that the entire sampling frame (map) is classified. In many forest surveys where the area is too large to stratify completely, double sampling for stratification is used (Cochran 1977). A large first-phase sample is taken and classified, typically using aerial photography, to estimate the stratum sizes (weights). The second phase is then drawn from the first-phase sample by strata, much like stratified random sampling. The variance estimators are similar, but the double sampling for stratification estimator includes a term to account for the estimation of the unknown weights. In either case, proportional allocation is recommended for permanent surveys because it adapts better to changes in objectives and changes in stratification over time.

For example, the USDA Forest Service's Northeastern Forest Inventory and Analysis (FIA) unit combined double sampling for stratification and SPR (Bickford et al. 1963). At the first measurement occasion, a grid of plots on aerial photographs was classified into land-use and timber-volume strata. A subsample of these was measured on the ground. At the second occasion, a subsample of the ground plots was remeasured. A new grid of plots on new imagery was classified into strata. A subsample of these was selected for ground measurement. Thus, two independent sets of stratum weights and ground samples were drawn. The estimates of current values were computed by combining estimates from the independent samples. Change estimators for this two-occasion case and the extension to three occasions were presented by Scott and Köhl (1994). This design combines the power of double sampling for stratification, with the flexibility of SPR to optimize for estimation of current values and change simultaneously.

Some work has been done in forestry on multiphase and multistage sampling. With multiphase sampling, additional levels from which to subsample plots are added, such as from satellite photos and high-altitude photos (see Schreuder et al. 1995). With multistage sampling, large primary sampling units are selected at the first level, such as on satellite images. Then subsamples are drawn from each of the primary sampling units, such as on aerial photographs. Then subsamples of each of those are drawn, such as plots on the ground. W. E. Frayer (1979, Multilevel sampling designs for forest inventories, *unpublished report*) developed estimators for both forms of multilevel sampling. Although it is difficult to detect change from satellites with these methods, they do hold promise for cost-effective estimates of current values.

Sampling frequency

Forest surveys typically are conducted on a 5–20 yr cycle, with faster growing areas on a shorter cycle. There is increasing interest in shorter survey cycles due to reductions in rotation ages for timber harvesting, as well as other human influences on forest resources. In two current FIA studies, researchers are focusing on an annual forest inventory system (AFIS) that would provide yearly estimates but with less precision than a periodic survey. Because the latter loses precision during the time between surveys, on average, AFIS may prove more useful. It also would provide annual observations to detect change in the resource rather than simply estimating periodic change. More frequent surveys also help build relationships between disturbance events and the ecosystem responses. Disturbance is key to ecosystem composition, structure, and function. For this reason, the Forest Health Monitoring (FHM) program in the Northeast has visited clusters annually (Scott et al. 1993). Other regions have favored using a 4-yr rotation sampling design that results in four times as many clusters in a region as well as a 4-yr measurement cycle. These are the kinds of trade-offs survey planners must make given the limited resources available to them.

Plot Designs

Once the sampling design is chosen, the next step is to choose a sampling unit (plot design) that can be used to efficiently estimate change. Plots are characterized by shape, size, selection rule (e.g., probability proportional to frequency vs. size), and observational units (fixed area vs. individual trees). Forest surveys often use circular plots, while research studies often use rectangular plots. The shape issue is more one of field efficiency than of ecology. Plot size is a key factor in determining the efficiency of the plot design. As plot size increases, within-plot variance increases and between-plot variance decreases, resulting in a smaller variance estimate across all plots. However, as the size increases, so does the cost. Nevertheless, plot sizes must also be tied to the ecological scale of the attribute and must be large enough to characterize or classify the plot accurately, such as for a diversity index.

The selection rule used most often for monitoring is probability proportional to frequency, i.e., all observational units (such as trees) within a fixed area are selected. For example, a fixed-radius plot often is used to sample trees to estimate the number of trees and volume per hectare. Although variable-radius or Bitterlich plots are efficient for current values and some change values, they are not recommended for permanent plots (Scott and Alegria 1990). Also, this method poses problems with respect to estimating components of change (Gregoire 1993).

Plot clusters

In extensive forest surveys, clustering plots can be a cost-effective technique. Clusters are characterized by the kinds of plots they contain, the number of plots, their size, and their spatial arrangement. Clustering as used here differs from classical cluster sampling in that the cluster is the sampling unit of interest in forestry, while it is the individual within the cluster that is of interest in social surveys. For example, regeneration can be sampled on four 0.001-ha plots, each concentric with a 0.1-ha plot for overstory trees, with each plot center spaced 50 m apart on the vertices of a square. Clustering provides the opportunity to "spread out" the sampling unit; thus, more "independent" or "new" information is collected at each location vs. simply measuring one large plot. This reduces the between-cluster variance. Thus, the number of clusters needed to meet a specified precision level is reduced. The trade-off is that it costs more to set up separate plots. In extensive surveys, much of the cost (often 50%) is for travel to the cluster, so it is more efficient to sample one large cluster than attempt to sample two small clusters in a single day (Arvanitis and O'Regan 1972, Scott 1993). When sampling intensities are high and travel between clusters is on foot, single-plot clusters probably are more efficient. Thus, the first question is: How many clusters can reasonably be visited within a single day? The second is: What cluster design best uses the time left after traveling?

The reduction in variance that results from increasing the number of plots, their size, and spatial arrangement differs by attribute (Nyyssonen et al. 1971). Some, such as area attributes, respond best to a large number of widely spaced plots. Others, such as growth, tend to respond best to several large plots (Scott 1981). The plot and cluster design has an important impact on the efficiency of change estimates.

In forest surveys, estimates from both plots and clusters of plots typically are expressed on a per-hectare basis for the cluster as a whole. The cluster observation is simply the average of the plot observations. Thus, the "within-cluster" variation is not relevant in forestry applications. Therefore, the variance is computed between the cluster observations.

Analytical Methods

Current values and changes in those values can be estimated with classical estimators appropriate to temporary and CFI designs. As stated earlier, temporary surveys cannot be used to estimate components of growth and other attributes that can be observed only on permanent plots. Any change estimates must be computed as the difference between the two occasions, and the variance of a difference is the sum of the variances.

With SPR, there are many more estimation alternatives. Ware and Cunia (1962) used classical estimators (assumed variances and covariances were known). Bickford et al. (1963) applied Meier's (1953) sample-based variance estimator to improve the variance estimate of a combined estimate. Scott and Köhl (1994) extended the estimation to include stratification and up to three measurement occasions. Cunia (1965) set the estimation in a multiple regression framework, and Newton et al. (1974) introduced multivariate regression estimators. However, these last two methods introduce problems with sample-based estimation (Newton et al. 1974, Scott 1984).

Van Deusen (1989) used generalized least squares (GLS) to address the problem of sample-based variance estimation in a regression framework. His approach provides efficient estimators for current values, net change, and components of growth, and even improves previous values. Dixon and Howitt (1979) applied the Kalman (1960) filter to improve estimates of both current values and change with SPR. They used growth models as prior information to make predictions, which were then combined with sample data to form more precise estimates. The mixed estimation approach of Theil (1971) is similar to the GLS approach, but provides a means of including growth projections, much like the Kalman filter.

Each of these analytical methods seeks to improve the precision of the estimates. With each refinement comes added complexity, which entails real costs. Scott (1986) discussed some of the problems encountered when using SPR estimators. With several thousand clusters, three independent estimates from three occasions, and hundreds of tables, it is not feasible for FIA to monitor individual regressions to ensure that the resulting model is appropriate. Any errors detected in the results are much more difficult to resolve, and the data set is less useful to other researchers and analysts.

As the estimators become more complex, so does variance estimation. After several years of experience with the SPR variance estimators, I often found that the independent estimates from each occasion resulted in confidence intervals that did not overlap. The estimates derived from the regression equations tended to have much smaller variances than would be expected. Thus, bootstrapping or jackknifing methods were used to test the sample-based variances used by Bickford et al. (1963) and Scott (1984). However, the classical estimators proved reliable (Schreuder et al. 1987). Currently, a similar test is being conducted on the mixed estimator that uses a simple diameter-growth model for predictions. Again, the variance of the predictions is smaller relative to the sample-based estimates, thus pulling the estimates to the predicted values. If the model is not correct, the results can be disastrous.

Attribute Selection

The attributes observed or computed from observations are the primary keys to addressing the questions or objectives of the survey. In permanent forest surveys, attributes that have proven valuable are soils, percent slope, terrain position, land use, land cover, stand age, tree species, diameter, height, tree history, distance, and direction to the tree.

Effects vs. stressors

These attributes provide information on forest status and changes but no information on stressors, only effects. This has been characteristic of forest surveys until the last decade or so. Other extensive surveys have focused on single stressors, such as gypsy moths and other insects and diseases, and their effects on specific aspects of the forest ecosystem.

More intensive surveys have addressed the effects of stressors, such as atmospheric deposition, on forested ecosystems. In 1990, the FHM program developed an extensive survey to detect the effects of a wide range of stressors. Data on stressors are collected on site or from other sources. This is an example of a significant attempt to combine multiple stressors with a suite of forest-ecosystem effects.

Challenges

Although much has been done to identify attributes that are good indicators of ecosystem function and health, few have proved reliable, repeatable, and cost effective. Research on identifying ecosystem indicators should be given high priority. But even if we find the "right" attributes, is change detectable over the years that the surveys are being conducted? On the basis of gap-phase models, David Reed (*personal communication*) predicts that change in species composition due to global change will not be detectable for 100 yr. This technique of using prediction models can be used to help address some key questions. What sample sizes are needed, and can we afford them? How often must we sample to capture significant but short-term events, such as defoliation or an ice storm? These issues must be addressed when monitoring for change.

Conclusions

Forest resource monitoring methods have been successfully used for estimating change for decades. However, many factors must be considered when monitoring for change in forest resources. The sampling design must be representative of the population of interest over time and result in precise estimates of change and its components. Over the years, focus has shifted from assessing current values and net change to understanding the dynamics of the components of net change. For this reason, I recommend a permanent-plot system (CFI) using a systematic grid. If stratification is used with it, I recommend that a time-invariant stratification be used. The Ecological Classification System (ECOMAP 1993) uses a hierarchical framework in which only the lowest level or two depend on current vegetation. However, the classification uses climate, landform, and other factors that are related to vegetative composition. As a result, this system or similar approaches should prove superior to land-cover class for stratifying permanent-plot systems. Proportional allocation of plots to strata also is recommended. An alternative to permanent stratification is using a permanent grid of samples, with new stratification applied as new information becomes available. This approach also leads to proportional allocation.

Permanent fixed-area plots are preferred over temporary or variable-radius plots, thus providing direct estimates of the components of change. Where plots are spaced far enough apart that the crews travel from one to another, as in extensive forest surveys, the plots should be clustered to improve efficiency. The number and size of the different plot types within the cluster can be modified in relation to one another to develop an optimum design that neither under- nor oversamples any attribute.

Additional research is needed on the optimal frequency of surveys and on their spatial scale. Different ecosystem processes operate at different temporal and spatial scales. The planner must determine the key processes and identify the longest survey cycle that still meets the need. More work is needed on how to sample landscape processes and interactions as part of an extensive forest resource survey, although multistage sampling holds promise.

With virtually all long-term studies or surveys, the objectives and questions asked of them have changed over time. Thus, the design must be robust, that is, it must be near optimal for many characteristics. I recommend simple sampling designs for this reason. Such a choice also leads to simple estimators, which would make the data accessible to more researchers. This is not to say that more sophisticated estimators such as GLS and mixed estimation cannot be used, only that they are not required.

Finally, high priority should be given to the development of indicators of forest-ecosystem health. Current measures tend to be subjective and do not lend themselves to change estimation. Also, most quantitative measures are not yet cost effective. Surveys also must be designed in ways that combine observations of multiple stressors and their effects on the sustainability of our forest resources.

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