Considerations in Forest Growth Estimation Between Two Measurements of Mapped Forest Inventory Plots

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Abstract.—Several aspects of the enhanced Forest Inventory and Analysis (FIA) program's national plot design complicate change estimation. The design incorporates up to three separate plot sizes (microplot, subplot, and macroplot) to sample trees of different sizes. Because multiple plot sizes are involved, change estimators designed for polyareal plot sampling, such as those used for horizontal point sampling, is still required. The differences between two such estimators FIA has favored in the past are discussed. The condition-class mapping feature of the new design further complicates change estimation. These complications are discussed, and alternatives to simplify the design are proposed.

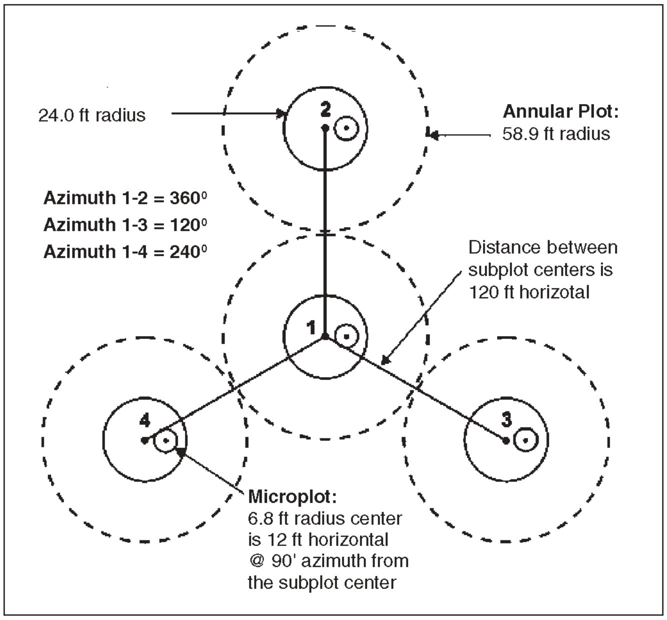
Introduction

The U.S. Department of Agriculture Forest Service Forest Inventory and Analysis (FIA) program uses a mapped, fixed-plot design as part of its national core sampling protocols (Hahn *et al.* 1995). Each ground plot contains a cluster of four points spaced 120 feet apart (fig. 1). Each point is surrounded by a 24-foot, fixed-radius subplot where trees 5.0 inches diameter at breast height (d.b.h.) and larger are measured. All four subplots total approximately 1/6th of an acre. Each subplot contains a 6.8-foot, fixed-radius microplot where saplings (1.0–4.9 inches d.b.h.) and seedlings are measured. All four microplots total approximately 1/75th of an acre. Each subplot is surrounded by a 58.9-foot, fixed-radius macroplot, which can be useful for sampling rare occurrences such as large trees (e.g., greater than 40.0 inches d.b.h.). All four macroplots total approximately 1 acre.

To enable division of the forest into various domains of interest for analytical purposes, the tree data recorded on these plots must be properly associated with the area classifications. To accomplish this, plots are mapped by condition class. Field crews assign an arbitrary number (usually 1) to the first condition class encountered on a plot. This number is then defined by a series of predetermined discrete variables attached to it (i.e., land use, forest type, stand size, regeneration status, tree density, stand origin, ownership group, and disturbance history). Additional conditions are identified if a distinct change occurs in any of the condition-class variables on the plot.

Sometimes a plot straddles two or more distinct condition classes. Boundaries between condition classes can bisect the subplots, or they can be located between the subplots. Microplots and macroplots (if used) are mapped in a similar fashion. Thus,

Figure 1.—*Basic plot design.*



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for each ground plot, the microplot, subplot, and macroplot area in each condition class is known, as are the location and condition class of every tree tallied.

One objective of the FIA program is to assess forest growth (gross growth, net growth, and net change) and forest change (land clearings, reversions and encroachment, forest condition changes). The mapped-plot design introduced new challenges in change assessment. This article examines the situations unique to the mapped-plot design and discusses considerations that may affect estimates of forest growth and forest change.

Forest Growth

FIA generally recognizes at least four components of growth; these are usually expressed in terms of growing-stock or all-live volume, where t is the initial inventory of a measurement cycle, and $t + 1$ is the terminal inventory, and are listed as follows:

S = survivor growth—the change in volume of live trees at time t that survive until time $t + 1$.

I = ingrowth—the volume of trees at the time that they grow across the minimum diameter threshold between time t and time $t + 1$. The estimate is derived at the size of trees at the threshold (1.0 inch d.b.h. for all-live volume and 5.0 inches for growing-stock volume). The diameter thresholds are usually measured at breast height, but for shrub-like trees designated as "woodland species" in the Western United States, diameter at root collar (d.r.c.) is the measure employed. Growth on ingrowth is the change in volume of ingrowth trees between the time they reach the threshold diameter and time $t + 1$.

M = mortality—the volume of trees that die due to natural causes between time t and time $t + 1$.

C = cut—the volume of trees that were removed due to harvesting activity between time t and time $t + 1$.

These components are used to explain the difference in inventory volumes (V_t and V_{t+1}) between time t and time $t + 1$. One desirable feature in broad-scale inventories is change estimators that are additive (i.e., the previous inventory plus the net change sums to the new inventory). To be additive, the estimators for each component of growth on the right side of the equation (Meyer 1953),

$$V_{t+1} - V_t = S + I - M - C,$$

must sum to the difference of the estimators of the left side values. This additive feature is referred to as *compatibility*. Total compatibility in broad-scale inventories is never ensured, however, partly because of intersurvey population differences caused by additions to or deletions from the forest land base, protocol changes (e.g., species added or deleted), and previous misclassifications by field crews.

FIA usually reports estimates of change for growing-stock volume (live trees 5.0 inches d.b.h. and larger at time t that meet the definitions of growing stock). For the growing-stock case, only the subplot is used in the estimation process at time t and time $t + 1$, so most estimators reduce to the same result. Some regions, however, use the optional macroplot. Situations also exist in which the attribute of interest is all-live volume (where the diameter threshold is 1.0 inch) and requires data from the microplot. If both the microplot and subplot are involved, the plot design is biareal; if the macroplots are also involved, the plot design is triareal. Any change estimation involving more than one plot size is polyareal sampling, and the same techniques required for permanent horizontal point sample apply.

FIA units have historically used one of two methods for computing change from horizontal point samples—the methods proposed by Beers and Miller (1964) and Van Deusen *et al.* (1986). These and several other estimators were considered for use in FIA's National Information Management System. The Beers-Miller estimator was ultimately selected as the national default for FIA because of its intuitive simplicity (Bechtold and Patterson, in press).

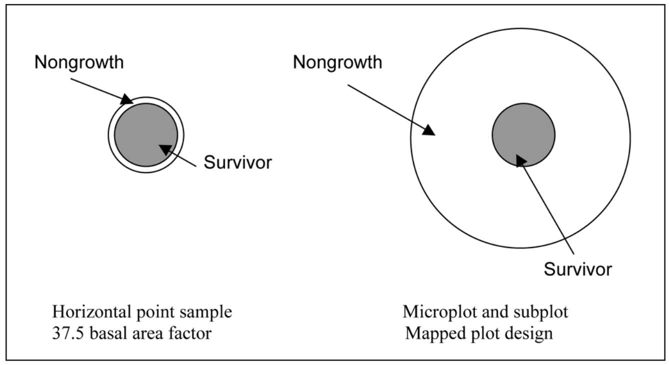
The Beers-Miller estimator weights all survivor growth (S) on the plot size at time t, which is analogous to "fixing the plot size" at the time of the initial inventory. This estimator excludes "nongrowth trees" from the definition of survivor growth. Nongrowth trees are defined as subplot trees outside the microplot and at least 5.0 inches in diameter at time $t + 1$ and at least 1.0 inch at time t. The Van Deusen estimator weights S based on the plot size where growth occurs (i.e., at time t and time $t + 1$) and includes nongrowth trees. This procedure was preferred by some FIA units because of the compatibility attained by incorporating the nongrowth trees excluded by the Beers-Miller procedure.

Roesch (1988) outlines a procedure that "fixes the plot size" at the end of the inventory period. The procedure includes nongrowth trees, and their growth is estimated. For FIA inventory purposes, the procedure would predict the attributes for computing a nongrowth's tree volume at time t, such as d.b.h. and bole length. The procedure is considered unbiased if the estimator of the time t values of the trees in the nongrowth sample is unbiased.

Although all three techniques are unbiased, the Beers-Miller approach has been criticized because of its lack of compatibility. The previous inventory plus the net change do not sum to the current inventory because all the weighting is based on initial tree size to compensate for the exclusion of the nongrowth component. If compatibility was a major concern for at least some FIA regions when traditional horizontal point samples were used, it continues to be an issue for FIA's current biareal and triareal plot designs. If one is interested in using the information contained in the sample of nongrowth to attain compatibility, one should consider an estimator other than the Beers-Miller approach.

Figure 2 illustrates the relative selection circles for trees that were less than 5.0 inches d.b.h. at time t and grew to a d.b.h. of 5.1 inches at time $t + 1$ for a horizontal point sample and the FIA's biareal design (microplot and subplot). The shaded inner circle represents the initial selection probability of a microplot (1/300th of an acre) for both plot types. The outer circle represents the terminal selection probability. For a horizontal point sample with a basal area factor of 37.5, a 5.1-inch d.b.h. tree would represent approximately 264 trees per acre, whereas the same size tree would represent 24 trees per acre on the subplot. The abrupt drop in the per acre value for a S tree growing from the

Figure 2.—*Selection circles for nongrowth trees for a horizontal point sample and a microplot and subplot for the mapped plot design.*



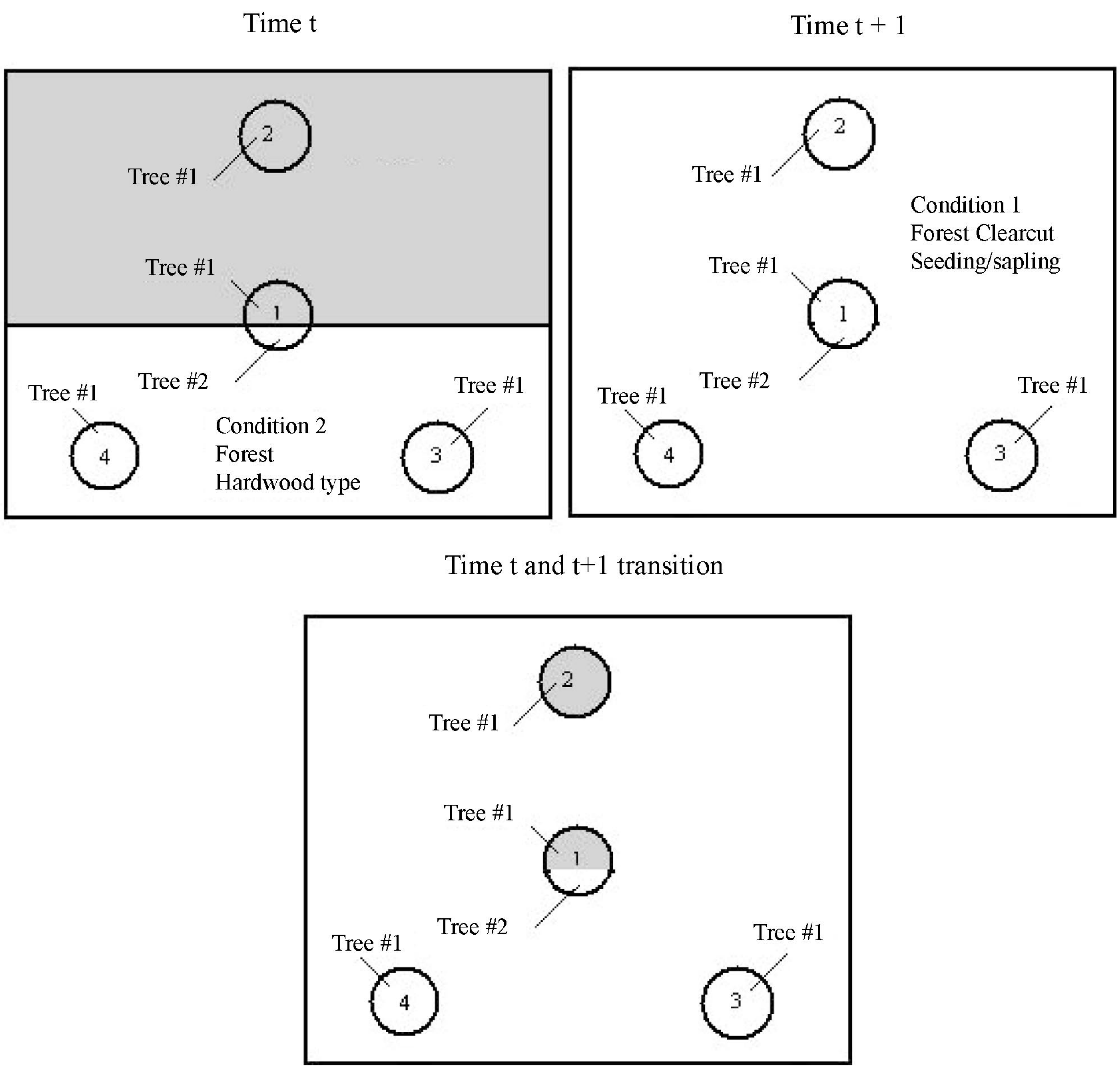
microplot on to the subplot would result in a significant negative survivor growth value for an individual tree if the Van Deusen approach was used.

The magnitude of the difference between growth estimators will depend on the number of trees in the nongrowth sample representing additional information. If the population of trees is varied, and nongrowth trees are only a small part of the population of interest, all three growth procedures should yield about the same estimate of survivor growth. Suppose instead that the population of trees is even-aged, and the basal areas of the trees are heavily clustered about the threshold between the microplot and the subplot. In this latter case, the nongrowth sample becomes significant. This situation is fairly common in regions where intensive forest management produces young, rapidly growing, planted pine stands.

The mapped-plot design poses another challenge for forest growth estimates because the shape and area of condition classes change over time. This design complicates the partitioning of growth, removals, and mortality by condition-class parameters at either time t or time $t + 1$. Summarizing timber removal volume by condition -class parameters such as forest type, stand origin, and ownership at the time of the initial inventory is usually desirable in broad-scale reporting.

Consider the following example. Figure 3 illustrates a situation where at time t, a plot was separated into two forest conditions, a hardwood and a softwood stand. Between time t and time $t + 1$,

Figure 3.—*Example of condition classes at time t, time t + 1, and associated transition matrix.*



Time t				**Time t + 1**			
Subplot	Tree	Condition	Status	Subplot	Tree	Condition	Status
1	1	1	live	1	1	1	cut
1	2	2	live	1	2	1	live
2	1	1	live	2	1	1	cut
3	1	2	live	3	1	1	cut
4	1	2	live	4	1	1	cut

the stand was harvested resulting in one condition at the second visit. The table in figure 3 indicates the subplot, tree number, condition number, and tree status assignment at the two points in time. The shaded area in the time *t* and time *t* + 1 transition illustration indicates the position of the two previous conditions in relation to the current condition. Visually, a condition class transition matrix is produced by overlaying a map of each subplot at time *t* with a similar map of the same subplot at time *t* + 1. A population estimate of removal volume by previous forest type requires a condition indicator assigned at time *t* to all trees assigned a tree status of cut at time *t* + 1.

The previous condition numbers of all remeasured trees are automatically available from the data collected at time *t*; however, in some cases the assignment of previous condition to new trees (missed, ingrowth, and nongrowth trees) requires additional effort. The assignment of previous conditions to new trees can be automated for subplots that had no boundaries at time *t*, but for subplots with previous boundaries, the previous condition numbers of new trees may need to be assigned in the field. This aspect of mapped plots has the potential to increase measurement error associated with change estimation. The extra fieldwork could be avoided by using a computer algorithm such as the one developed by Bechtold *et al.* (2003), which uses geometry to superimpose a previous condition map over the coordinates of new trees, but at least some of the automated assignments (i.e., trees close to boundaries) still need to be manually checked when the data are processed.

In addition to the extra fieldwork and/or processing requirements, another major consideration associated with the mapped plots is how the database will be structured for temporal comparisons. Linking plot-level, condition-level, or tree-level data between two points in time can be cumbersome, if not impossible, if certain coding schemes change. Adopting a procedure that may not be as accurate but eases the burden on the information management effort may be simpler.

The following two alternatives for assigning a previous condition to remeasured trees would eliminate the need for a complicated simulation procedure and be simple to apply in the field or office:

1. Plot-level approach. All remeasured trees on the plot at time *t* + 1 are assigned the condition value of plot center at time *t*. The condition assignment to a remeasured tree remains the same at time *t* + 1. A slight modification to this approach would be to assign a condition value associated with the predominant condition at time *t*—i.e., the previous single condition with the highest area percent of the plot area. This would alleviate the occasional situation where a road, right-of-way, or other small feature passes through plot center.
2. Subplot-level approach. All remeasured trees on the plot at time *t* + 1 area are assigned the condition value at subplot center at time *t.* The condition assignment to a remeasured tree remains the same at time *t* + 1. A slight modification to this approach would be to assign a condition value associated with the predominant condition at time *t*—i.e., the previous single condition with the highest area percent of the subplot area. This would alleviate the occasional situation where a road, right-of-way, or other small feature passes through subplot center.

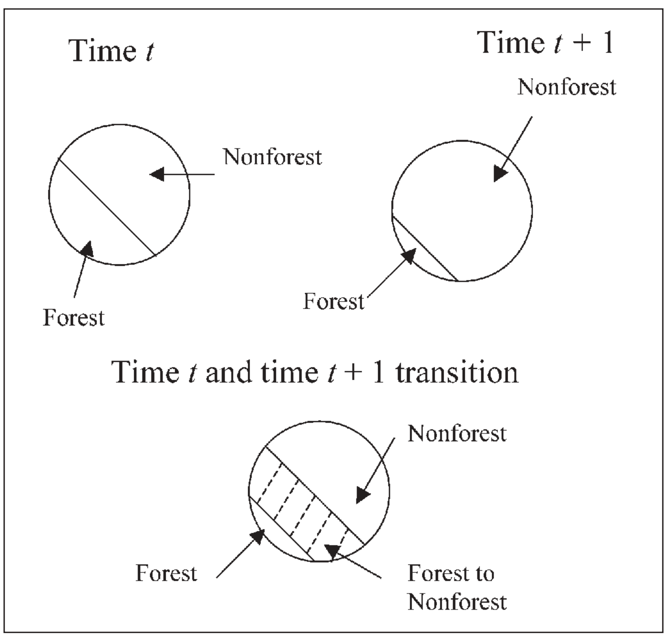
Forest Area Change

Forest area change may be defined as the difference in the aggregate acreage of forest or stand area based on the remeasurement of the same area at two points of time. FIA typically uses a two-phase sampling approach for estimates of forest area where a large sample of photo points or pixels are interpreted to assign strata for a smaller sample of ground plots (Cochran, 1963. Quantifying changes in forest populations over time is usually accomplished by changes measured on field plots. Having a measure of new forest land coming into the land base (such as reversions and encroachment) and forest land leaving the land base (such as forest land being converted to urban or agricultural land use) are often desirable, as is tracking certain stand conditions over time for ecological monitoring and trend analysis. For example, FIA has often produced estimates of acres harvested, regenerated, or disturbed for various stand classifications such as forest type, stand origin, and ownership. Estimates associated with change are usually stratified by the classification assigned at time *t*.

The procedures to accomplish forest area change estimates are similar to those described for assigning remeasured trees to condition class, except the attribute of interest is area instead of volume. Figure 4 illustrates a common occurrence in which the edge of a forest-nonforest boundary has changed between two points in time on a subplot, a typical situation along the edges of agricultural fields or alongside roads where small amounts of forest land have been cleared. The crosshatched area in the time *t* and *t* + 1 transition indicates the actual area that has been cleared. If this small amount of land area can be quantified, and an area percent can be developed, this proportion could be applied to a total land area figure to determine the amount of acreage that was cleared.

If the plot map from time *t* + 1 is superimposed over the map from time *t* to estimate change, several considerations become evident. First, a distinction between real change, field crew error, and measurement error must be made. Subtle changes in boundary delineation due to measurement error could result in absurdly small change polygons that are meaningless for analysis purposes. In the figure 4 example, suppose the change was due to nothing other than field crew error at time *t* or time *t* + 1?

Figure 4.—*Example of forest land being cleared on a subplot, with condition classes at time t, time t + 1, and associated transition matrix.*



Should error be treated as real change, or should it be identified and corrected? Second, because an infinite number of shapes are possible when a subplot mapped at time *t* is overlaid with its counterpart at time *t* + 1, database management could become unwieldy if condition-level observations are needed for every polygon created by change. Third, scale is always an important consideration in broad-scale inventories. Does FIA really need to identify small areas at a scale smaller than a subplot? Is it worth the time and effort to develop the field procedures, algorithms, simulation techniques, and databases to accommodate very small changes that occur on plots or subplots?

The following are two alternatives to the fully mapped approach:

1. Plot-level approach. All forest area change estimates are based on the assignment of the condition value at plot center at time *t* and time *t* + 1. The approach assumes only one condition exists at the plot level at both points in time. A slight modification to this approach would be to assign a condition value associated with the predominant condition at time *t* and time *t* + 1—the single condition with the highest area percent of the plot area. This would alleviate the occasional situation where a road, right-of-way, or other small feature passes through plot center.
2. Subplot-level approach. All forest area change estimates are based on the assignment of the condition value at subplot center at time *t* and time *t* + 1. The approach assumes only one condition exists at the subplot level at both points in time—up to four per plot location. A slight modification to this approach would be to assign a condition value associated with the predominant condition at time *t* and time *t* + 1—the single condition with the highest area percent of the subplot area. This would alleviate the occasional situation where a road, right-of-way, or other small feature passes through subplot center.

Discussion

Several possible estimators are available for growth of survivor trees when the fully mapped plot design is remeasured. Whatever procedure is selected, incorporating computation of two or more of the estimators in the analysis of remeasured mapped plot design data is suggested. Further analysis may be needed when evaluating trends in components of change. Many regions will be comparing estimates of growth, removals, and mortality from remeasured mapped plot data to estimates from earlier inventories in which horizontal point samples were used.

The alternative procedures suggested for quantifying forest change and assigning a previous condition classification to trees would simplify the data compilation process, but they have shortcomings. The plot-level approach can obviously result in bias in classification of change. For instance, a plot that is subdivided into a pine and hardwood condition at time *t* could result in significant numbers of trees being assigned to an incorrect condition classification (such as softwoods getting assigned to a hardwood forest type). The plot-level approach could yield acceptable results in regions with broad-scale homogenous conditions where very little condition changes are occurring on the plots. The subplot-level approach will give a more refined estimate of forest change than the plot-level approach assuming that boundary mapping on subplots is not occurring frequently. The most comprehensive evaluation of different alternatives should consist of compiling inventory data for a large region or a State and analyzing differences in population estimates using the different approaches including available mathematical simulation techniques.

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