Comparison of Annual Inventory Designs Using Forest Inventory and Analysis Data

Stanford L. Arner, James A. Westfall, and Charles T. Scott

ABSTRACT. Three annual inventory designs, a periodic design, and a periodic measurement with midcycle update design are compared using a population created from 14,754 remeasured Forest Inventory and Analysis plots. Two of the annual designs and the midcycle update design allow updating of plots not measured using sampling with partial replacement procedures. Comparisons are based on root mean square error and estimator bias determined for net volume (m^3/hectare) and mean annual net volume change. For the annual designs, both individual year and moving average estimates are investigated. The latter are compared to both the population means of the most recent year used in the average and to population means covering the same period as the estimate. Among annual designs, a rotating panel design, in which an equal portion of the total sample is measured each year without remeasurement until the start of the next measurement cycle, produced the smallest root mean square error for estimates of mean net volume. For multiple-year comparisons, the rotating panel and periodic designs resulted in the smallest root mean square errors; for single-year comparisons, the periodic design resulted in the smallest root mean square error. For mean annual volume change, the smallest root mean square error was produced by the periodic design. Among annual designs, the rotating panel design resulted in the smallest root mean square error for multiple-year comparisons of volume change, while a design allowing annual updates of estimates using generalized least squares resulted in the smallest root mean square error for single-year comparisons. FOR. SCI. 50(2): 188–203.

Key Words: Rotating panel design, moving average estimates, generalized least squares.

THE INVENTORIES OF THE NATION'S FORESTS by the Forest Inventory and Analysis (FIA) units of the USDA Forest Service provide forest managers and other users with information on the current status and changes in the forest resource. Until recently, these inventories have been implemented by applying a periodic inventory to each state. In response to several concerns, especially the increasing length of the measurement interval (hereafter referred to as the cycle) caused by reductions in funding and a lack of consistency in procedures and estimates among FIA units, the Agricultural Research, Extension, and Education Reform Act of 1998 (PL 105–185) called for a portion of the inventory of the nation's forests by FIA to be conducted annually within each state rather than a single periodic survey.

There are numerous possibilities for both the design of an annual system and the analysis procedures used; see, for example, Scott et al. (1999). We evaluate three designs with

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annual measurement of plots as well as a periodic design and a periodic design with midcycle update. These nonannual designs are included for comparison with past procedures and for evaluation as possibilities because the legislation allows each state the option of retaining a periodic inventory. A nonannual inventory might be appropriate for small states, which might have very few plots measured each year in an annual inventory.

The annual designs considered here as well as the midcycle update design allow estimation procedures that use information from plots not measured in a particular year. The estimation procedures evaluated in this study are a moving average estimator, and estimators based on sampling with partial replacement (SPR) using generalized least squares (Scott 1984). Modeling procedures using growth models such as TWIGS (Miner et al. 1988) or the imputation models described by Van Deusen (1997) are not evaluated in this study.

Procedures

In this study, we compare the estimates obtained with each design using a "known" population. Repeated random samples are drawn from the population and results for each design and estimation procedure are evaluated for accuracy, as expressed by root mean square error (RMSE), and for bias, as estimated by the mean difference of the sample estimates from the population mean. Both RMSE and bias are presented and discussed as a percent of the population value. Two variables are evaluated; net volume (m^3/hectare) and mean annual change in net volume between measurements. Net volume is the volume of live trees of commercial species at least 12.7 cm (5 in.) in diameter at breast height after cull volume has been deducted (Griffith and Alerich 1996). Cost is not evaluated directly, though an attempt is made to control for cost by requiring the measurement of the same number of plots by each design during a measurement cycle.

Creation of the Population

The population is based on 14,754 remeasured inventory plots for the most recent inventories of Pennsylvania, New York, Maine, Vermont, New Hampshire, West Virginia, Kentucky, and Massachusetts; 10,669 plots were classified as forest at the initial measurement and 10,643 were forest at the last measurement. The interval between initial and final measurement ranged from 8 to 14 years, with most states being measured during the 1982–1998 time period.

For this study, a time series of 15 measurements was generated for each plot, and a volume was assigned to each of the 13 years between the first and last measurements. The method of volume assignment depended on the measurement characteristics of the individual tree:

1. Trees recorded and alive for both initial and final measurements (survivor trees) were assigned these measurements to year 1 and year 15, respectively, and were assumed to change in volume at a constant rate. The assumption of a constant rate of change in net volume for an individual tree was made to reflect the values reported for growth components by FIA (mean annual volume change) and to avoid the complexity of modeling net volume change, which would require an accounting of changes in quality. The use of the 14-year interval for all trees regardless of the actual measurement interval resulted in a small reduction in annual volume change for most plots, because more than 97% of the plots had a 12- to 14-year period between measurements. The impact of these procedures on the relative values of the statistics used to compare the designs should be small.
2. Trees not recorded at the initial measurement (ingrowth and ongrowth) or not alive at the final measurement (removals and mortality) were assigned a year of entry or exit from the inventory at random. For ingrowth, ongrowth, and mortality, the year was determined for each tree individually. If removals occurred, the same removal year was assigned to all removal trees on the plot. The volumes of ingrowth and ongrowth trees, from the year of entry until year 15, and of removal trees, from year 1 to 1 year prior to removal, were assigned based on a simple linear growth model developed using survivor trees. For each of the 18 species groups used by the Northeast FIA (NEFIA), an annual volume increment was predicted by 10.2-cm (4-in.) diameter class for both initial and final diameter. Annual volumes were then calculated using initial or final diameter, the predicted volume increment based on the model developed using either initial or final diameter, and the assumption of a constant growth rate. To reflect the probable reduced vigor of mortality trees, they were assumed not to grow between initial measurement and the year of death.

The values for individual trees were then summed to obtain a total net volume for each plot for each of the 15 years. Annual volumes for these 14,754 plots were used as the population.

Inventory Designs

Three annual inventory designs were considered, as were a periodic design and a periodic design with midcycle update. For this study, a 7-year remeasurement cycle was assumed, i.e., for a particular design, years 1, 8, 15, etc. began the same 7-year plot measurement pattern. The designs differ in the measurement pattern of the random sample of plots taken from the population. For each design, the sample was divided randomly into predetermined groups defined by the years of measurement during a cycle. The number of plot groups, sample size of each group, and thus the plot assignment to a group varied by design. Within each design, each group retained the same measurement pattern through successive cycles.

The sample size used in this study was based on a sampling fraction of 0.08, resulting in 1,180 plots. Although the sampling fraction is not nearly as small as that currently in place by NEFIA (approximately one plot per 2,428 ha of land within each state), the number of plots is representative of the sample size for most states; 8 of the 13 states have fewer than 1,180 plots, ranging from 111 to 5,037. To gain insight into the possible effect of sample size, a sample of 442 plots resulting from a sampling fraction of 0.03 also was investigated. As expected, bias was unaffected by sample size, while RMSEs were substantially less for the larger sample. Because there was little difference in the relative values of the RMSEs for the two sample sizes, results for the larger sample only are presented.

Because an attempt was made to approximate equal costs among the designs by requiring an equal number of plot measurements during a cycle, 1,180 is actually the total number of plots measured in one cycle. For designs involving remeasurement of a portion of the plots during a cycle, the total number of different plots in the sample was less than 1,180.

Estimation Procedures

The model for each design can be expressed in terms of plot-group assignment and years of measurement of each group within a cycle. The notation is based on that used by Scott et al. (1999).

Notation

n_g = number of plots in group g

g = index used to indicate a partition or group of plots with the same measurement pattern during an inventory cycle

G = total number of plot groups in an inventory design

i_{gt} = measurement indicator of plot group at time t
$= \begin{cases} 1, \text{ if group } g \text{ is measured at time } t \\ 0, \text{ otherwise} \end{cases}$

$n.(t)$ = number of plots measured at time t, plot group not considered
$= \Sigma_{g=1}^{G} ng{\cdot}igt$

$y_{gm}(t)$ = net volume (m^3/hectare) of plot m in plot group g at time t

$\bar{y}_{gm}(t)$ = mean net volume for plot group g at time t
$= \Sigma_{m=1}^{n_g} y_{gm}(t)/n_g$

$\bar{y}.(t)$ = mean net volume of all plots measured at time t
$= \Sigma_{g=1}^{G} \Sigma_{m=1}^{n_g} y_{gm}(t) \cdot i_{gt}/n.(t)$

$\bar{y}.(t, l)$ = mean net volume of l most recent measurements at time t
$= \Sigma_{j=t-l+1}^{t} \Sigma_{g=1}^{G} \Sigma_{m=1}^{n_g} y_{gm}(j) \cdot i_{gj}/\Sigma_{j=t-l+1}^{t} n.(j), l \leq t$

$\bar{Y}(t)$ = population mean net volume at time t

$\bar{Y}(t,l)$ = population mean net volume for the l most recent years,
$= \Sigma_{j=t-l+1}^{t} \bar{Y}(j)/l, l \leq t$

$\bar{c}_g(t-j,t,l)$ = mean annual volume change for plot group g between time $t-j$ and t determined using averages of length l

$\bar{c}_g(t-j,t,l)$ = mean annual volume change between time $t-j$ and t determined using averages of length l across all plot groups
$= (\bar{y}.(t, l) - \bar{y}.(t-j, l))/j, l + j \leq t$

$\bar{C}(t-j,t)$ = population mean annual volume change between time $t-j$ and t
$= (\bar{Y}(t) - \bar{Y}(t-j))/j, j \leq t.$

Several estimation procedures were investigated for each design.

Design 1: Rotating Panel

In the rotating panel design, each plot is randomly assigned to one of the seven equal groups. One plot group is measured each year and is then remeasured every seventh year (see Table 1). This is the least complex of the annual procedures considered here and, using a 5-year cycle, is the design used by the Southern and North Central Research Stations, and the Northeastern Research Station in Maine. Because there is no remeasurement within a cycle, the total number of unique plots sampled is 1,180, with 168 measured each year. For this study, the four remaining plots needed to reach the 1,180 total were assigned to a group at random.

Because there are no matching measurements among different groups of plots, SPR procedures cannot be used to

Table 1. Rotating panel design, 7-year cycle.

		Year														
		Cycle 1							Cycle 2							
Plot group	No. plots	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	168	X							X							X
2	168		X							X						
3	168			X							X					
4	168				X							X				
5	168					X							X			
6	168						X							X		
7	168							X							X	
Total	1,176	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168

update the plots not measured in a particular year. Simple estimates of the population mean can be obtained each year by calculating the mean of the group of plots observed that year. Because of the relatively few numbers of plots for individual years, it was thought that using several years' mean volume in a moving average procedure could improve the estimates. Three-, 5-, and 7-year simple moving averages were investigated using $\bar{y}.(t, 3)$, $\bar{y}.(t, 5)$, and $\bar{y}.(t, 7)$, respectively. Also investigated were volume change estimates, $\bar{c}.(t-1, t, l)$ for $l = 1, 3, 5$, and 7. Each $\bar{c}.(t-1, t, l)$ is the difference between successive l-year moving average estimates of net volume. Note that for the rotating panel design $\bar{c}.(t-1, t, l)$ is equivalent to $\bar{c}.(t-l, t, 1)$ when the sample sizes are the same for each panel. After the start of the second cycle, volume change can be estimated using remeasured plots. Also, if the pattern of measurement as designed is not retained, then the volume change estimate determined using remeasured plots only is not equivalent to the difference determined using the two means, $\bar{y}.(t)$ and $\bar{y}.(t-7)$.

For estimating the most recent 1-year volume change, $\bar{c}.(t-1, t, 1)$ directly uses the data for the interval of interest, while $\bar{c}.(t-7, t, 1)$ takes advantage of the correlation between measurements on the same plots at different times. The estimate $\bar{c}.(t-1, t, 1)$ is compatible (i.e., numerically consistent) only with $\bar{y}.(t, 1)$; thus, if compatible estimates were desired, the advantage of additional plots using multiple-year averages would be lost. Also, although not considered in this study, components of change such as ingrowth, mortality, and removals are estimated using remeasured plots. Thus, the use of $\bar{y}.(t, 1)$ and $\bar{c}.(t-1, t, 1)$ will result in estimates that are not compatible with the components of growth. In fact, the only estimates for which all components of growth are compatible are those that use averages with the number of years equal to the cycle length, $\bar{y}.(t, 7)$ and $\bar{c}.(t-1, t, 7)$, with the same set of plots and land area measured at both time t and $t - 7$. Although compatibility is only one consideration for deciding on the estimates to use, incompatibility of estimates has caused some confusion in the past.

Design 2: Balanced Annual Partial Remeasurement

With this design, an equal number of plots is measured each year, all plots can be used to obtain estimates for the current year, and for designs measuring an equal number of plots each year of the cycle, the maximum number of plots are remeasured each year. For a 7-year cycle, 21 plot groups of equal size are required, each with a different measurement pattern (Table 2). Six of the groups are measured each year; by the last year of the first cycle, each group of plots is remeasured with the interval ranging from 1 to 6 years. The most recent measurement year of each of the groups not used in a particular year is the same as the first measurement year of one of the groups that is remeasured. Thus, information for all plots can be updated using SPR procedures. As an example, in year 8, plot group 6 can be used to update the year 7 values of plot groups 11, 15, 18, 20, and 21, and plot group 5 can be used to update the year 6 values of plot groups 10, 14, 17, and 19.

Each sample plot is assigned to one of the 21 plot groups at random. Because all plots are remeasured once during a

Table 2. Balanced annual partial remeasurement, 7-year cycle.

		Year														
		Cycle 1							Cycle 2							
Plot group	No. plots	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	28	X	X						X	X						X
2	28	X		X					X		X					X
3	28	X			X				X			X				X
4	28	X				X			X				X			X
5	28	X					X		X					X		X
6	28	X						X	X						X	X
7	28		X	X						X	X					
8	28		X		X					X		X				
9	28		X			X				X			X			
10	28		X				X			X				X		
11	28		X					X		X					X	
12	28			X	X						X	X				
13	28			X		X					X		X			
14	28			X			X				X			X		
15	28			X				X			X				X	
16	28				X	X						X	X			
17	28				X		X					X		X		
18	28				X			X				X			X	
19	28					X	X						X	X		
20	28					X		X					X		X	
21	28						X	X						X	X	
Total	588	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168

cycle, the total number of different plots is 590. Thus, all but 2 of the 21 groups contain 28 plots so that 168 plots are measured each year. The 2 extra plots needed to obtain 1,180 plot measurements per cycle for this study were assigned to a plot group at random, resulting in an extra 1 or 2 total plots in a year that those plot groups were measured.

As with the rotating panel design, simple averages at 1-, 3-, 5-, and 7-year intervals can be calculated, though the variances for these estimates are expected to be greater than for the rotating panel design because there are fewer plots used for the estimates. For the moving averages, only the most recent observation for the plot was used. The associated volume change over l years was estimated as the difference between successive averages, $\bar{c}.(t-1, t, l)$.

The advantage of this design is its ability to update all plots not measured at time t to a time t value using SPR procedures. The estimation procedure used a generalized least squares (GLS) approach similar to that presented in Van Deusen (1989) and Lynch (1995), and used by Scott et al. (1999). The model can be expressed as

$$\bar{y} = XU + \bar{e} \tag{1}$$

where for year t

$\bar{y}$	=	vector of group means with elements $\bar{y}_g(t-i)$ for $i = 0$ to 6 and $g = 1$ to 21
X	=	design matrix of ones and zeros indicating measurement of group g in year $t-i$
U	=	vector of population means for years $t-6$ through t
	=	$[\bar{Y}(t-6), \bar{Y}(t-5), Y(t-4), \bar{Y}(t-3), \bar{Y}(t-2), \bar{Y}(t-1), \bar{Y}(t)]$
$\bar{e}$	=	vector of errors with elements $e(\bar{y}_g(t-i))$ for $i = 0$ to 6 and $g = 1$ to 21
$e(\bar{y}_g(t-i))$	=	error of the mean for plot group g at time $t-i$
$E(\bar{e}\bar{e}')$	=	Σ.

If group g is remeasured in year t then $\bar{y}$ contains both $\bar{y}$ and $\bar{y}_g(t)$ and $\bar{y}_g(t-i)$, where $t-i$ is the most recent previous measurement year. If group g is not remeasured in year t, then $\bar{y}$ contains $\bar{y}_g(t-i)$ only. If the plot groups are ordered by measurement year $t-i$, then Σ is a block diagonal matrix with six elements, Σ_{t-i}, where Σ_{t-i} is the covariance matrix for the plot groups whose most recent measurement prior to year t is $t-i$. As an example, Equation 1 in the Appendix displays the model for year 8 and Equation 2 in the Appendix displays Σ_{t-i} for $t = 8$ and $i = 4$.

The GLS estimator of U is

$$\hat{U} = (X'\Sigma^{-1}X)^{-1}X'\Sigma^{-1}\bar{y} \tag{2}$$

with variance

$$V(\hat{U}) = (X'\Sigma^{-1}X)^{-1}. \tag{3}$$

This is the best linear unbiased estimator if Σ is known.

Because Σ will not be known, sample-based estimates need to be substituted, so that the estimated variance of $\hat{U}$ is

$$v(\hat{U}) = (X'\Sigma^{-1}X)^{-1}. \tag{4}$$

The elements of each Σ_{t-i} comprising Σ in Equation 6 were estimated using only the remeasured plots in group $t-i$. This is a modification of Scott et al.'s (1999) procedure in which they calculated the variances and covariances for each group using only the observations in that group. Most RMSE's were slightly less with this procedure than those resulting from the use of Scott's procedure.

Average annual change in volume can be estimated by constructing contrast vectors, D, and multiplying by the vector of estimated volumes,

$$\bar{c} = D\hat{U}. \tag{5}$$

The variance of $\bar{c}$ is estimated as

$$v(\bar{c}) = Dv(\hat{U})D'. \tag{6}$$

Several estimators for mean annual volume change were investigated. At time t, the GLS procedure produces estimates of mean volume for the seven most recent years. One estimate was to use only the parameters estimated for years t and $t-1$, so that $D = [0,0,0,0,0,-1,1]$. A second was to determine an average of all six volume differences. The jth element of D is $-1/((7-j)\cdot 6)$ for $j = 1$ to 6; the seventh element is $\Sigma_{j=1}^{6} 1/((7-j)\cdot 6)$.

Design 3: Regional Periodic Measurement with Annual Update

The entire area to be inventoried is divided into regions of equal size, with the number of regions equal to the cycle length. The inventory then cycles through the regions with each having a large periodic measurement once during a cycle. During years for which the large inventory is not taken, a subset of the plots measured in the periodic year is remeasured (Table 3). This design should result in estimates with small variance in a region once during a cycle due to the large sample, and allow this large sample to be updated each year. Although this design might be implemented so that there are seven regions within each state, for this study it was assumed that each region was a state or group of states, and that estimates were desired for each state individually. Thus, the 1,180 plot measurements per cycle were applied to an individual region.

All but one plot group are defined by the number of years after the periodic measurement that the plots in that group are remeasured. Thus, the plots in group 3 are remeasured 3 years after the periodic measurement. The seventh plot group has only the periodic measurement. There is a tradeoff between the proportion, R, of plots remeasured in update years and the total number of plots. An increase in R results in smaller variance for the update estimates, but also reduces the total number of plots, and thus increases the variance of the periodic estimate. Although other values of R were used, the value of R used for the results reported here was 0.4 or 472 plots that were remeasured during a cycle. This included 78 remeasured plots in each of the update years with the extra four

Table 3. Regional periodic measurement with annual update, seven regions and 7-year cycle.

			Year													
			Cycle 1							Cycle 2						
Region	Plot group	No. plots	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	240	X							X						
	2	78	X	X						X	X					
	3	78	X		X					X		X				
	4	78	X			X				X			X			
	5	78	X				X			X				X		
	6	78	X					X		X					X	
	7	78	X						X	X						X
Total		708														
2	8	240		X							X					
	9	78	X	X						X	X					
	10	78		X	X						X	X				
	11	78		X		X					X		X			
	12	78		X			X				X			X		
	13	78		X				X			X				X	
	14	78		X					X		X					X
3	15	240			X							X				
	16	78	X		X					X		X				
	17	78		X	X						X	X				
	18	78			X	X						X	X			
	19	78			X		X					X		X		
	20	78			X			X				X			X	
	21	78			X				X			X				X
4	22	240				X							X			
	23	78	X			X				X			X			
	24	78		X		X					X		X			
	25	78			X	X						X	X			
	26	78				X	X						X	X		
	27	78				X		X					X		X	
	28	78				X			X				X			X
5	29	240					X							X		
	30	78	X				X			X				X		
	31	78		X			X				X			X		
	32	78			X		X					X		X		
	33	78				X	X						X	X		
	34	78					X	X						X	X	
	35	78					X		X					X		X
6	36	240						X							X	
	37	78	X					X		X					X	
	38	78		X				X			X				X	
	39	78			X			X				X			X	
	40	78				X		X					X		X	
	41	78					X	X						X	X	
	42	78						X	X						X	X
7	43	240							X							X
	44	78	X						X	X						X
	45	78		X					X		X					X
	46	78			X				X			X				X
	47	78				X			X				X			X
	48	78					X		X					X		X
	49	78						X	X						X	X
Total		4,956	1,176	1,176	1,176	1,176	1,176	1,176	1,176	1,176	1,176	1,176	1,176	1,176	1,176	1,176

plots assigned to years at random. The value of *R* chosen is a compromise between the conflicting consequences of changes in *R* and resulted in 708 plots in a region, which was between the 590 plots of the balanced annual partial remeasurement design that has complete remeasurement and the 1,180 plots of the rotating panel design that has no remeasurement during a cycle. If all plots were remeasured, the last plot group would be dropped and the total number of plots would be 590. Although the number of plots measured each year within a region was not constant, with equivalent sampling intensities for all regions, the total number of plots measured across all regions would be the same each year. Each sample plot is assigned to one of the plot groups at random.

We need different updating models for periodic and nonperiodic years. For periodic years, two estimation procedures were considered. The first estimated mean volume with the simple mean of the current periodic measurement, and estimated mean annual volume change using the difference between the current and previous periodic means. The other procedure used GLS to determine the estimates of a model similar to Equation 2 of the balanced annual partial remeasurement design, containing the periodic and each of the seven most recent prior measurements. Mean annual volume change was estimated with the average of the seven volume differences.

For update years, a two-parameter GLS model representing the volume of the current update year and the previous periodic year was used to update all plots from the most recent periodic measurement. Mean annual volume change was estimated as the difference between the parameters estimated divided by the period length between measurements.

Design 4: Periodic Measurement

All plots are measured in the same year of the cycle (Table 4); for a 7-year cycle over 15 years, this would be years 1, 8, and 15. The large sample should result in the smallest variance for estimates of current volume for the periodic measurement years, and for change in volume between successive measurements. However, the confidence that these estimates are a good representation of the resource declines with increasing time since measurement.

Estimates of mean volume were obtained by calculating the simple means of the periodic measurements. Mean annual volume change was estimated as the difference between the periodic means divided by the cycle length. Until the start of the second cycle, mean volume for years 2 through 7 can be estimated with the mean volume for year 1,

$$\bar{y}.(t+i) = \bar{y}.(t) \quad \text{for } i = 1 \text{ to } 6, t = 1. \qquad (7)$$

However, once the second cycle is begun, other estimates for the years between measurements can be obtained via linear interpolation. For inventory years $t - 7$ and t, mean volume for the intervening 6 years can be estimated by

$$\bar{y}.(t-7+j) = \bar{y}.(t-7) + \bar{c}.(t-7, t, 1)\cdot j \quad \text{for } j = 1 \text{ to } 6, t = 8, 15, \ldots \qquad (8)$$

Mean volume for the 6 years following year t can be estimated using

$$\bar{y}.(t+j) = \bar{y}.(t) + \bar{c}.(t-7, t, 1)\cdot j \quad \text{for } j = 1 \text{ to } 7. \qquad (9)$$

Design 5: Periodic Measurement with Midcycle Update

A full inventory is taken in a single year as in the periodic design. Also, a subset of plots is remeasured midway between two periodic measurements. For the 7-year cycle, years 5 and 12 were used as the update years. Table 5 shows the sampling scheme for this design covering 15 years with a 7-year cycle.

The decline in confidence with increasing time since the periodic measurement could be interrupted midway between the large inventories by using the remeasured plots to update the periodic inventory. Although the other designs were investigated with an equivalent number of plot measurements during a cycle, the midcycle update was implemented for this study by remeasuring 10% of the 1,180 plots measured for the periodic design. Thus, this design had a greater number of plot measurements during a cycle so that costs are not directly comparable with the other designs. This was done to investigate improvement to the periodic design with a midcycle update.

As for the regional periodic measurement with annual update design, different updating models are needed for periodic and update years. In periodic years, mean volume and mean annual volume change can be estimated using the mean volumes of the current and previous periodic years; or estimates can be determined using GLS for a model containing two groups and three parameters. One group would contain the mean volumes of the current periodic and previous update years and the second would contain the mean volumes of the current and previous periodic measurements. The parameters estimated are the mean volumes for the previous update, previous periodic, and current periodic years.

As for the balanced annual partial remeasurement design, several estimates of mean annual volume change were investigated. One was to calculate the mean annual difference between the estimated volumes for the prior update and most recent periodic years, and a second was to calculate mean annual difference between the estimates of volume for the current and previous periodic years.

For update years, the remeasured plots were used to update those not remeasured from the most recent periodic year. As for the regional periodic measurement with annual update design, the GLS model contained two groups and

Table 4. Periodic measurement, 7-year cycle.

		Year														
		Cycle 1							Cycle 2							
Plot group	No. plots	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1,180	X							X							X

Table 5. Periodic measurement with midcycle update, 7-year cycle.

Plot group	No. plots	Year														
		Cycle 1							Cycle 2							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	118	X				X			X				X			X
2	1,180	X							X							X
Total	1,298	1,298				118			1,298				118			1,298

two parameters representing the mean volumes of the current update and previous periodic years. Mean annual volume change was estimated as the difference between the two estimates of mean volume divided by the period between measurements.

Analysis

The designs were compared by drawing repeated random samples from the population of 14,754 plots, applying the sample to each design, determining estimates for each design and estimation procedure, and comparing the estimates to the population values. The basis of evaluation was accuracy, as expressed by RMSE, and estimator bias, calculated as the mean difference between the estimates and the population values from 1,000 iterations of the sample/estimation procedure and expressed as percent of the population mean being estimated. One thousand iterations were used even though bias and mean square error (MSE) stabilized at about 200 iterations. The start of the second cycle was used because it was desirable to make comparisons based on equivalent time periods, and because some estimates cannot be determined for some designs until the start of the second cycle. It also was desired to base comparisons at full implementation to avoid startup differences. Accuracy and bias are presented in most of the tables as a percent of the 8-year average of the population values being estimated.

Means for individual years, moving averages, and GLS estimates for both volume and mean annual volume change were evaluated with these statistics. Estimates determined for an individual year were compared with population values for that year. Moving average estimates of length l were compared with the population value of the final year, and with population means covering the same interval as the moving average. The remaining discussion refers to these as "single-year" and "same-length" comparisons, respectively. The average of multiple years of observations is an unbiased estimate of the average condition of the resource for the period equivalent to the estimate. Estimates of average annual volume change determined using a span of more than 1 year also were compared with both the "single-year" population mean annual volume change, $\bar{C}(t-1), t)$, and "same-length" population mean annual volume change, $\bar{C}(t-l), t)$, where l is the length of the period on which the volume change estimate is based.

Results

Rotating Panel Design

Table 6 shows the percent biases and RMSEs of the estimates of mean volume for both same-length and single-year comparisons of 1-, 3-, 5-, and 7-year moving averages over years 8 through 15. The estimator bias for same-length comparisons was less than 0.15% for each of the averages. However, the time lag bias for single-year comparisons increased with increasing length of the average, as well as over time (Table 7). These biases reflect the nature of the increasing values over time for the population (Figure 1). The increase in bias with increasing length of the moving average contrasts with the reduced RMSEs with increasing length seen in Table 6. Although the bias contribution to MSE was greater than 50% in year 15 for the 7-year moving average, the information contributed by the additional plots compensated for the increase in bias. The 7-year moving average had the lowest RMSEs for both same-length and single-year comparisons (Table 6).

Kish (1998) suggests that weighted averages may be used to provide more up-to-date estimates when combining data over multiple years of measurement (see Alexander 2002). In the context of this research, improved estimates of current volume might be obtained by applying larger weights to the more recent years of the moving average estimates. Using this approach, the weighted mean net volume of l most recent measurements at time t would be given by:

$$\bar{y}.(t, l)_w = \sum_{j=t-l+1}^{t} w_j\bar{y}.(j) \quad l \leq t \quad \text{where} \quad \sum_{j=t-l+1}^{t} w_j = 1 \tag{10}$$

The results for single-year comparisons using five sets of weights are presented in Table 8. There was an increase in RMSE for both mean volume and mean annual volume change with increasingly larger weights for the recent years. This is not surprising when the nature of the sample and population are considered; the average difference between the mean volumes determined each year for individual iterations, disregarding sign, was 6.4 m^3/ha, while the average yearly change in the population over the 15 years was 0.5 m^3/ha (Figure 1). Applying larger weights to recent years increased the tendency of the estimates to follow the fluctuations of the individual panels, as opposed to the smoothing effect of simply including more plots.

Single-year comparisons for mean volume change showed an increase in estimator bias and a decrease in RMSE with increasing length of period used to estimate volume change (Table 9). RMSE also decreased with increasing period length for same-length comparisons. Note

Table 6. RMSE and bias of net volume for years 8 through 15 combined (percent of population mean).

Comparison type	Moving average length	Rotating panel	Balanced annual partial remeasurement: Simple means	Balanced annual partial remeasurement: GLS	Regional periodic measurement with annual update: Simple means	Regional periodic measurement with annual update: GLS	Periodic	Midcycle update
		(% RMSE)						
Single year	1	7.4	7.4	4.3	9.7	4.4	2.7	3.3
	3	4.3	4.9	4.2	6.0	3.8		
	5	3.5	4.4	4.4	4.9	3.8		
	7	3.3	4.3	4.9	4.6	4.0		
Same length	3	4.3	4.9	4.1	6.0	3.8		
	5	3.2	4.2	4.0	4.8	3.6		
	7	2.7	3.9	4.0	4.1	3.6		
		(% Bias)						
Single year	1	0.1	0.1	−0.2	0.0	0.1	0.4	−0.8
	3	−0.6	−0.7	−1.1	−0.8	−0.6		
	5	−1.3	−1.4	−2.0	−1.5	−1.3		
	7	−1.8	−1.9	−2.9	−2.0	−1.8		
Same length	3	0.1	0.1	−0.2	0.0	0.1		
	5	0.1	0.1	−0.2	0.0	0.2		
	7	0.1	0.1	−0.2	0.0	0.2		

Table 7. Rotating panel design: bias of moving average from population mean net volume of the final year (percent of population mean).

Year	Moving average length: 1	3	5	7
	(% Bias)			
8	0.42	−0.17	−0.52	−0.92
9	0.23	−0.42	−0.70	−1.11
10	−0.33	−0.58	−1.05	−1.41
11	0.22	−0.74	−1.33	−1.70
12	0.41	−0.78	−1.43	−1.96
13	0.51	−0.62	−1.64	−2.35
14	−0.43	−0.76	−1.76	−2.47
15	0.20	−0.93	−1.82	−2.74

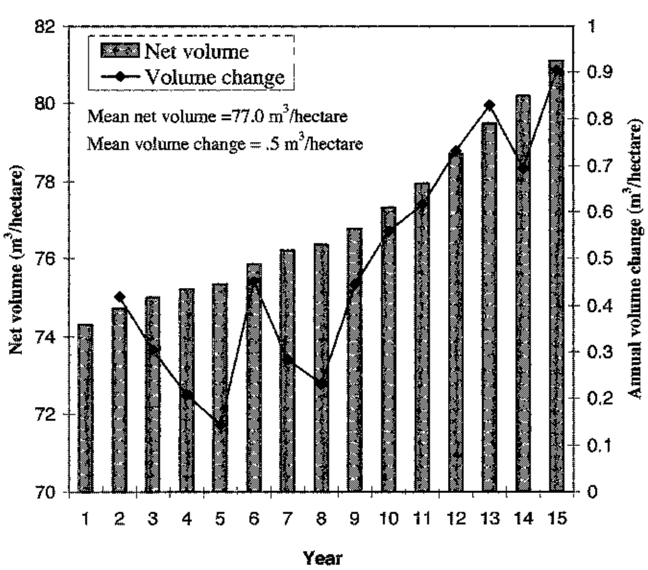

Figure 1. Population mean net volume (m^3/ha) and annual volume change, 14,754 plots.

Table 8. Rotating panel design: bias and RMSE of weighted 7-year mean net volume when compared to population value of the final year (percent of population mean).

Weights applied	Volume: % Bias	Volume: % RMSE
0.14, 0.14, 0.14, 0.14, 0.14, 0.14, 0.14	−1.8	3.3
0.20, 0.20, 0.20, 0.10, 0.10, 0.10, 0.10	−1.5	3.2
0.25, 0.25, 0.20, 0.10, 0.10, 0.05, 0.05	−1.2	3.4
0.30, 0.30, 0.20, 0.08, 0.06, 0.04, 0.02	−0.9	3.6
0.30, 0.25, 0.20, 0.15, 0.05, 0.03, 0.02	−1.0	3.5
0.30, 0.25, 0.15, 0.12, 0.08, 0.06, 0.04	−1.1	3.4

the sharp drop in RMSE when the period length increases from 5 to 7 years for both types of comparisons. The estimates of mean annual volume change for the 7-year period were based on a single panel of remeasured plots. Thus, for estimating volume change between the most recent 2 years, the 7-year difference based on remeasured plots resulted in substantially lower RMSE than volume

Table 9. RMSE and bias of mean annual volume change for years 8 through 15 combined (percent of population mean).

Comparison type	Moving average length	Rotating panel	Balanced annual partial remeasurement: Simple means	Balanced annual partial remeasurement: GLS	Regional periodic measurement with annual update: Simple means	Regional periodic measurement with annual update: GLS	Periodic	Midcycle update
		(% RMSE)						
Single year	1	1,317.0	1,198.7	86.6	1,755.6	124.6	29.1	66.1
	3	439.8	398.8	52.3	570.1	75.6		
	5	259.6	242.9	46.9	340.6	64.3		
	7	64.9	65.8	48.0	80.0	61.1		
	3–7[a]	49.0						
Same length	3	487.9	442.2	55.8	632.2	80.5		
	5	324.9	303.5	49.1	426.6	70.8		
	7	77.6	78.1	46.8	101.1	66.7	19.7	
	5–7[b]	35.6						
		(% Bias)						
Single year	1	9.9	5.5	2.5	–0.6	–12.7	–1.5	–9.8
	3	–10.5	–11.1	–11.6	–10.7	–20.8		
	5	–18.9	–22.3	–23.3	–22.1	–27.6		
	7	–29.5	–30.7	–31.9	–30.1	–32.6		
	3–7	–39.7						
Same length	3	–0.7	–1.3	1.9	–0.9	–12.1		
	5	1.9	–2.4	1.0	–2.2	–9.1		
	7	–1.4	–3.0	2.4	–2.2	–5.6	–1.5	
	5–7	–23.3						

[a] 3–7 = 3 panels of remeasured plots.
[b] 5–7 = 5 panels of remeasured plots.

change estimated using the most recent 2 year's volume estimates.

To see if extending the measurement interval to include additional panels of remeasured plots would further reduce RMSE, mean annual volume change was calculated using three, five, and seven sets of remeasured plots. These estimates were then compared to both the 7-year population mean annual volume change and the most recent year's mean volume change (Table 10). For estimating change in volume between the most recent 2 years as well as the most recent 7 years, three panels of remeasured plots produced a further reduction in RMSE; for single-year mean volume change, additional panels beyond three showed no improvement; for 7-year mean annual volume change, the RMSE was lowest with five sets of plots. However, increasing the number of panels of remeasured plots also increased the estimator bias for both types of comparisons. It should be noted that for this study, $c.(t-7, t, l)$ can be calculated for the years beginning with $t = 7 + l$; thus, the percentages for same length comparisons presented in Table 10 are based on means beginning with year $t = 7 + l$.

Balanced Annual Partial Remeasurement

For mean volume, the balanced annual partial remeasurement design resulted in the same pattern of increasing estimator bias for single-year comparisons with increasing length of the moving average estimator as the rotating panel design (Table 6). All same-length comparison biases were less than 0.15% of the population mean volume for years 8 through 15.

Without moving averages, the GLS procedure produced substantial improvement in RMSE over the simple means estimator of mean volume. Although the 3-year moving average of GLS estimators resulted in a slightly lower RMSE than the 1-year GLS estimate, longer-length averages produced little improvement; in fact, the 5- and 7-year moving averages had increasing RMSEs for the single-year comparisons. It is interesting that the 7-year moving average of the simple means estimator resulted in a lower RMSE than most GLS estimators. For single-year comparisons, the 7-year simple mean RMSE of 4.3% was only slightly greater than the smallest RMSE for the GLS estimators, 4.2% for the 3-year average. Sample size probably was a major contributor to this outcome, which is similar to that observed for the rotating panel design. While all plots are used by both GLS and the 7-year simple mean, the GLS update is based on a subset of plots equal to the number of plots measured in a single year of the rotating panel design (6 of 21 of the plots are remeasured each year on half the

Table 10. Rotating panel design: percent RMSE and bias of mean annual volume change using multiple panels of remeasured plots for years 8 through 15 combined.

Comparison type	Number of remeasured panels	% Bias	% RMSE
Single year	1	–29.5	64.9
	3	–39.7	49.0
	5	–44.9	49.7
	7	–45.3	49.0
Same length	1	–1.4	77.6
	3	–12.6	41.8
	5	–23.3	35.6
	7	–31.1	37.2

total plots used for the rotating panel design). Year-to-year fluctuations in the estimates for the rotating panel design using this sample size were much greater than the yearly change in the population.

Unlike the estimates of mean volume, increasing the number of years included in a moving average resulted in reductions in RMSE for mean annual volume change (Table 9). A probable reason for this is the increasing number of sets of remeasured plots used in the estimation procedure. Also, for both same-length and single-year comparisons, and for each length of the moving average, the GLS procedure yielded lower RMSEs than the simple means procedure. However, the 7-year simple mean resulted in substantially lower RMSE of mean annual volume change than the GLS procedure without use of multiple-year averages. Again, the results for the rotating panel design might offer a possible explanation. Not only was RMSE for mean annual volume change lowest when remeasured plots were used, there also was a decrease in RMSE with an increase in the length of time between measurements used to estimate change in volume.

For the GLS estimator, volume change results are reported in Table 9 only for the estimator using an average of six contrasts involving year t and 6 prior years' volume estimates. This estimator produced substantially smaller estimator bias and RMSE than the contrast between the most recent 2 years' volume estimates; there are six times as many plots used to estimate mean annual volume change with the average of six contrasts estimator.

Regional Periodic Measurement with Annual Update

Like the previous designs, estimator bias for mean volume increased with increasing length of the average for single-year comparisons (Table 6). For the simple means procedure, the RMSE decreased with increasing length of the moving average for both same-length and single-year comparisons. For the GLS procedure there was little improvement in RMSE with moving average length greater than 3, and for single-year comparisons, the RMSE was greater for the 7-year moving average than for the 3- and 5-year moving averages. The RMSEs were less for the GLS procedure than for the simple means procedure for all moving average lengths.

In the analysis of volume change, an increase in the number of years averaged for the estimates resulted in an increase in bias for the single-year comparisons and a reduction in RMSE (Table 9). Like the previous designs, a probable reason for the RMSE reduction is the increase in the number of remeasured plots used in the estimation procedure. The 7-year average resulted in the smallest bias and RMSE for same-length comparisons.

Periodic Measurement

Beginning with the second measurement in year 8, three estimates of mean volume for the following nonmeasurement years were investigated. The first used the year 8 sample mean as the estimate for each of the following 6 years (Equation 9). The second used Equation 11 to update year 8 with mean annual volume change determined for the previous interval. The third updated year 8 with mean annual volume change determined with years 8 and 15 (Equation 10). This last estimate cannot be calculated until year 15 is measured and thus would be of interest for estimating the condition of the resource for the past 7 years.

The bias using Equations 9 and 11 became fairly large for the last several years of the measurement interval, with the contribution to MSE in excess of 50% for Equation 9 in year 14. The MSEs presented in Table 11 show the loss in accuracy with increasing time since the periodic measurement. The bias contribution to MSE was reduced substantially when mean annual volume change determined for the previous period was used in the estimator, while bias added little to MSE when mean annual volume change for the interval covering the years being estimated was included.

The estimator biases and RMSEs of mean volume for the years 8 through 15 combined for the three estimation procedures are presented in Table 12. Also included are the results for the measurement years 8 and 15 combined and the nonmeasurement years 9 through 14. The first three rows of Table 12 show the reduction in both bias and RMSE when the two volume change estimates were included in the estimator.

Table 11. Periodic design: reduction in bias contribution and MSE with volume change added to periodic volume.

	Estimator					
	$\bar{y}(8)$		$\bar{y}(8) + c(1,8)^a$		$\bar{y}(8) + c(8,15)^b$	
Year	% (Bias)^2	% MSE	% (Bias)^2	% MSE	% (Bias)^2	% MSE
8	0	77	0	77	0	77
9	2	79	0	80	2	78
10	15	91	2	85	4	80
11	42	117	8	95	5	81
12	91	166	22	112	4	81
13	169	243	48	143	2	80
14	252	326	74	174	1	82
15	0	83	0	83	0	83

[a] $c(1,8) = \bar{c}.(1,8,1) \cdot (\text{year} - 8)$.
[b] $c(8,15) = \bar{c}.(8,15,1) \cdot (\text{year} - 8)$.

Table 12. Periodic design: percent bias and RMSE for mean net volume.

Years of comparison	Estimation equation	% Bias	% RMSE
8 through 15	$\bar{y}(8)$	−1.9	3.6
	$\bar{y}(8) + c(1,8)^a$	−0.9	3.1
	$\bar{y}(8) + c(8,15)^b$	0.4	2.7
8 and 15	$\bar{y}(8), \bar{y}(15)$	0.1	2.7
9 through 14	$\bar{y}(8)$	−2.5	3.9
	$\bar{y}(8) + c(1,8)^a$	−1.2	3.2
	$\bar{y}(8) + c(8,15)^b$	0.5	2.7

[a] $c(1,8) = \bar{c}.(1,8,1) \cdot (\text{year} - 8)$.
[b] $c(8,15) = \bar{c}.(8,15,1) \cdot (\text{year} - 8)$.

Periodic Measurement with Midcycle Update

Although several analytical procedures involving combinations of midcycle and periodic measurements were investigated, the results presented in this report used the GLS procedure for midcycle years and the simple means for periodic years. Annual change in volume for the periodic years was estimated as the average annual change between periodic measurements. This procedure produced a smaller RMSE than the procedure that used more recent midcycle years in the estimator. The much smaller sample size for the midcycle years resulted in much higher variation in the estimates of mean volume, which carried over to the volume change estimates. An indication of this can be observed in Table 13, which shows that estimates of periodic volume change ending in midcycle years have a much larger RMSE than those ending in periodic years. Despite the higher variability for the update years, the use of GLS for these years resulted in lower RMSE for mean volume than the means procedure.

Design Comparisons

The choice of an inventory design depends on a variety of factors including but not restricted to accuracy and cost. Gillespie (2000) lists many of the advantages and disadvantages of an annual versus a periodic inventory in relation to the FIA program. Advantages of an annual design include the availability of the same amount and age of data at any point in time without regard to political boundaries. This makes possible analyses across a region of any size without the concern of different ages of data for different regions. Another advantage is the ability to measure the effect of catastrophic events such as hurricanes without the need to obtain additional funding for a special inventory between periodic samples.

There could be a cost savings by having field crews at fixed locations. This could reduce moving expenses and increase the retention period and experience of the crew members. On the other hand, additional personnel would be needed to compile the data for all states each year, and additional analysts would be needed to interpret and report on the status of the resources in a timely fashion.

Another disadvantage suggested by Gillespie is the relatively large year-to-year fluctuations of estimates using only the data for an individual year, resulting in a loss of confidence in the results by the users. This study showed that this disadvantage can be overcome with a moving average procedure.

The major advantage of the periodic design is the relatively low variance of the estimates at a particular point in time. A disadvantage is the unknown loss of confidence with increasing time since the last periodic measurement.

This study attempted to address the question of accuracy of estimates obtained with several inventory designs for a fixed cost and should be used in conjunction with the considerations cited for deciding on the most appropriate inventory procedure. Other factors addressed in this study that should be considered are estimator bias, length of period to be estimated, and whether emphasis should be placed on estimating volume or volume change. The annual design that resulted in the most accurate estimate of current mean volume (RMSE = 4.3%) and 1-year change in mean volume (RMSE = 86.6%) was the balanced annual partial remeasurement design. Thus, if volume were of primary concern, this design would require a 66% smaller sample than the rotating panel design (RMSE = 7.4%) for the same accuracy. If volume change were of primary concern, the increase in sample size needed for the rotating panel design would be substantially larger.

A higher accuracy as expressed by RMSE can be obtained if we are willing to accept some bias in the estimate of current volume and 1-year change in volume; the 7-year moving average of the rotating panel design resulted in the lowest RMSE (3.3%) for 1-year mean volume, while the 5-year mean for the balanced annual partial remeasurement design resulted in the lowest RMSE (46.9%) for 1-year mean volume change. Primary emphasis placed on estimation of current volume would mean a 24.6% reduction in

Table 13. Periodic measurement with midcycle update: comparison of periodic net volume change for each measurement interval.

	% Bias		% RMSE	
Measurement interval	Simple means	GLS	Simple means	GLS
1 to 5	0.7	3.3	183.2	178.6
5 to 8[a]	−10.8	−10.8	38.7	38.7
8 to 12	−4.4	−2.5	96.4	95.2
12 to 15[b]	−16.9	−16.9	23.7	23.7

[a] Estimator = $\bar{c}.(1,8,1)$.
[b] Estimator = $\bar{c}.(8,15,1)$.

sample size from the best of the two annual update designs (RMSE = 3.8%); emphasis on volume change would mean an 8.4% reduction in sample size from that required by the rotating panel design (RMSE = 49.0%).

It also is interesting to note the differences between the two annual update designs. When moving averages of GLS estimates were used, the regional periodic with annual update design resulted in lower RMSEs for current mean volume, while the balanced annual partial remeasurement design resulted in lower RMSEs for 1-year mean volume change.

The moving average procedure produces unbiased estimates of the population mean volume for the same period used in the estimates. Among annual designs, for estimating both 5- and 7-year mean volume, the rotating panel design resulted in the lowest RMSEs (3.2% and 2.7%, respectively). The 2.7% translates to a reduction in sample size of 43.7% based on the lowest RMSE (3.6%) of the other annual designs.

For volume change over a period of years, five sets of remeasured panels produced a lower RMSE (35.6%) for estimating 7-year mean annual volume change than the 7-year moving average for the balanced annual partial remeasurement design (46.8%), a reduction in sample size of 42.1%.

The most basic decision is whether to use an annual or periodic design. When the periodic measurement was used as the estimate of mean volume for each succeeding year, the increasing bias resulted in a loss of accuracy over time (Table 11), so that the RMSE (3.6%, Table 12) for the period from year 8 to 15 was greater than that obtained with the 7-year moving average of the rotating panel design (3.3%). However, when the year 8 periodic mean volume was updated with mean annual volume change for the previous period, bias was reduced resulting in a somewhat lower RMSE of 3.1%, or a sample size reduction of 11.7% from the rotating panel design. Updating year 8 with mean annual volume change for the current period resulted in the lowest RMSE (2.7%) and bias (0.4%). This RMSE is equivalent to that obtained for the measurement years 8 and 15 only.

If primary interest were in estimating mean volume over a period of years, the rotating panel and periodic designs would require the same sample size for a particular accuracy level, because both resulted in an RMSE of 2.7%. However, if primary interest were in estimating mean annual volume change over the period, the periodic design would require a substantially smaller sample. The lowest RMSE obtained by an annual design was 35.6% when five sets of remeasured panels were used to estimate 7-year mean annual volume change. The RMSE of 19.7% for the periodic design would mean a sample size reduction of 69.4%.

The midcycle update lowered the individual year RMSE of mean volume of the periodic design from 3.6 to 3.3%. However, the 3.3% is greater than the 3.1% obtained by updating the year 8 mean with volume change determined for the previous period. A larger sample for the update probably would improve the RMSEs for both mean volume and mean annual volume change (66.1%), which was substantially larger than for the periodic design.

Compatibility Considerations

The rotating panel design using the 7-year moving average for both mean volume and mean annual volume change is the only annual procedure considered in this study for which the estimates of all elements of the growth components are compatible. $\bar{y}.(t, 7)$ is an unbiased estimate of the 7-year population mean, $\bar{y}(t, 7)$, and $\bar{c}.(t-1, t, 7)$ is an unbiased estimate of 7-year mean annual volume change in the population, $\bar{C}(t-7, t)$. While $\bar{y}.(t, 7)$ uses all plots, and, as an estimate of $\bar{y}(t, 7)$, results in RMSE and bias comparable to that obtained for the measurement years of the periodic design, $\bar{c}.(t-1, t, 7)$ uses only one of the seven sets of remeasured plots and thus results in substantially greater RMSE for mean annual volume change than the periodic design. This study indicates that the use of additional panels of remeasured plots for the rotating panel design yields a further reduction in RMSE for mean annual volume change. However, bias increases, and the estimate of mean annual volume change is no longer compatible with estimates of mean volume, $\bar{y}.(t, 7)$ and $\bar{y}.(t-1, 7)$.

The two annual update designs result in volume change estimates that are not compatible with the estimates of volume determined for any two consecutive years. Although compatible estimates for the years included in the GLS procedure for year t can be determined using procedures similar to those presented by Van Deusen (1989) and Lynch (1995), the resulting estimates of volume and volume change will not be compatible with the estimate of volume obtained for the previous year, because different combinations of the same plots, as well as different plots, are used for the GLS estimates for time t and $t-1$.

In summary, although the rotating panel design produced estimates of the 7-year population mean volume that were comparable to those obtained for the measurement years of the periodic design, the RMSE (77.6%) for the estimate of mean annual volume change that is compatible with these estimates of mean volume was substantially greater than that obtained by the periodic design (19.7%) for the year 8 to 15 interval. All components of growth are compatible with the estimates for any two successive measurement years for the periodic design.

As a word of caution, the statements concerning the compatibility of the estimates for the rotating panel design are true only if each yearly panel has the same number of observations and the same plots are measured each cycle in the same measurement pattern. The statements about the periodic design are true only if the same plots are measured each cycle. If plots are added or dropped for either design, the estimates for all components will not be compatible.

Discussion

The initial and final values of each plot in the population used for this study were actual inventory data. The volume change for each tree was the change observed on these plots between the two measurements. However, the time of actual occurrence for the components of change such as ingrowth, mortality, and removals was different than that used for the population; the year in which a tree left or entered the inventory was assigned at random while the interval was stretched to 14 years for all plots. A constant volume growth rate was assumed for remeasured trees. This procedure probably resulted in a population with a more uniform year-to-year volume change than actually occurred. This approach may favor the GLS method to some degree, as GLS is based on a linear model.

The "population" was actually a sample covering the 1982–1998 time frame from a wide range of forest conditions occurring from Kentucky to Maine. The population had certain characteristics. In particular, mean volume was increasing, with the increase greater in the second half of the 15-year period than the first half. The results obtained in this study might be different for other conditions, e.g., a switch in the direction of volume change. Also, as the best estimates of volume change and volume (based on RMSE) were produced by different designs, the best procedure for the components of growth or for other variables might be different.

Different results may also be realized for smaller sample sizes. Particularly, the GLS and midcycle update approaches rely on having relatively large numbers of plots to adequately describe underlying relationships. Additional research is needed to assess the performance of the various designs in situations where estimation must be based on few sample plots.

The sampling designs evaluated are less complex than the FIA design. For instance, stratification was not considered in this study. The use of a simple forest-nonforest stratification should reduce the variance substantially. With forest plots considered separately, the correlation among measurements should be higher, resulting in improved GLS estimates. The results obtained by the GLS procedures might also be improved with better variance estimates or maximum likelihood as suggested by Van Deusen (1989). The sampling schemes are more complex for the two annual update designs than for the rotating panel design, so that change in sampling intensity with changes in funding might cause more difficulties in estimation. Estimation procedures also are more complex. In particular, the estimates of variance of moving averages will need to account for the covariance among the GLS estimates because the estimates included in the averages use different combinations of the same plots.

Finally, several general results should be emphasized. For the type of population in this study, with year-to-year volume change fairly constant, improvement in volume change estimates, as determined by RMSE, was a function of three factors:

1. Length of period used to determine mean annual volume change. At least up to the limit of the cycle length in this study, increasing the period between the two volume estimates used to determine mean annual volume change led to a reduction in RMSE. This was true for the rotating panel design when independent (nonremeasured) plots were used, and for the two annual update designs using the simple-means estimates. Longer periods reduced the effect of the fluctuations of the individual panels.
2. Use of remeasured plots. For the rotating panel design there was a sharp decrease in the RMSE when remeasured plots were used for both same-length and single-year comparisons. Although the estimates of mean volume using a single panel might be substantially different from the population value, mean annual volume change estimated with these correlated observations was more representative of population mean annual volume change than mean annual volume change estimated with independent sets of plots.
3. Sample size. An increase in the number of plots used for the estimate, especially remeasured plots, resulted in a decrease in RMSE. This was confirmed by the results for each design. For both annual update designs, increasing the number of years averaged for both simple means and GLS estimates increased the number of remeasured plots used and resulted in lower RMSE. For the midcycle update design, the RMSE was much lower when the sample for the periodic years were used to estimate mean annual volume change than when the much smaller midcycle sample was used. Finally, the RMSEs for both same-length and single-year comparisons were substantially less for the periodic design than for the rotating panel design using 1/7 of the plots.

When estimation was based on simple means, the rotating panel design generally out-performed the other annual designs for accuracy in net volume. This advantage was evident for both single-year and same-length comparisons of RMSE over the range of moving average lengths examined. Essentially, the rotating panel design is a series of independent surveys, which is known to be superior to partial remeasurement and update designs for accuracy of simple means estimates. Remeasurement and update designs are formulated for estimation methods (e.g., generalized least squares) that take advantage of correlations between remeasured plots, whereas the performance of the simple mean estimator does not use panel overlap. Thus, the panel design was more efficient when using simple means. However, when estimates were based on GLS updates, both the balanced annual partial remeasurement and regional periodic with annual update designs provided the greatest accuracy when the moving average length was less than 3 years. Estimation based on 5- and 7-year lengths favored the rotating panel design due to larger sample sizes. Bias increases for the three annual designs as the length of the moving average increases. Their bias is negligible when using the same-length approach. The periodic and midcycle update designs produced estimates as accurate as the best annual design, but at the expense of higher bias due to the interval length between measurements.

Trends in design performance for estimating mean annual volume change differed from those for net volume. For accuracy of simple means estimates, the rotating panel design remained superior to the regional period design. However, the balanced annual design was somewhat better than the rotating panel design. The balanced annual design estimates benefited by utilizing more recent remeasurements, whereas the rotating panel relied on differences between panels having a 7-year remeasurement period. Increasing moving average lengths did substantially improve accuracy of estimates for the panel design, but with rather large increases in bias. Again, GLS updating showed marked increases in estimation accuracy when compared to simple means, especially for the shorter moving average lengths. Unlike for volume, increasing moving average lengths for GLS estimates resulted in improved accuracy due to additional remeasurements. The accuracy of GLS estimates for the regional periodic design was less than those for the balanced design due to smaller remeasurement sample sizes during each interval. Bias for volume change was highest for the GLS estimate associated with the regional periodic with annual update design. The GLS estimate for the balanced annual partial remeasurement design exhibited bias comparable to the other designs. The volume change estimate from the periodic design was superior to the other designs for both accuracy and bias. No advantage was gained by implementing a midcycle update to decrease bias, as the reduced sample size resulted in increased variance in terms of RMSE. Estimates based on this design had bias and accuracy attributes that were similar to those of the annual designs.

As demonstrated by this research, the best inventory design is dependent on a number of factors, including measurement cycle length, the ability to update unmeasured plots, estimation methods, tolerance levels for accuracy and bias, the relative importance of current versus change values, and practicality of implementation. Other advantages and disadvantages of specific designs will need to be considered as well (Gillespie 2000, Köhl and Scott 2000). The importance of each factor should be evaluated in terms of the overall objectives of the inventory process.

Each design has its strengths and weaknesses. The periodic survey provides a very accurate picture at each survey. Its accuracy erodes with time, but only due to increased bias that often is relatively low. Thus, the periodic design should be avoided when the population is changing rapidly. The large sample size results in low variances, thus the combination can be efficient. Midcycle updating was designed to reduce the bias, but this reduction does not offset the large increases in variance due to the reduced sample size following the update, thus the net effect over the cycle may be a reduced accuracy level. The midcycle update design should only be considered when the population is changing rapidly or following a catastrophic event.

The regional periodic with annual update design using GLS is helpful for current values in the first few years of transition to the new design and good for change estimation. It may also be more cost-effective in some applications due to its regional component whereby plots are closer together. The balanced annual partial replacement design using GLS was even better for current values in the first few years of transition to the new design and better for change estimation. These two designs are the only ones that can produce unbiased results on an annual basis, thus are appropriate for use when the forests are changing rapidly. Once most of the panels are in place, the rotating panel design performs well for current attributes due to the large sample sizes versus the other annual designs. As expected, this comes at the cost of accurate change estimates.

Generally, the two primary components that influence the estimation bias and accuracy of the various sampling designs are the growth rate of the population and sample size. As the growth rate increases, the bias of the estimators increases due to greater differences between the average condition for the period relative to current values. Sample size does not affect the magnitude of bias. If minimizing bias is of primary concern, using GLS with either the balanced annual partial replacement or regional periodic with annual update designs would likely yield the best results. The rotating panel, periodic, and midcycle update designs should be avoided as bias increases with the length of the measurement interval.

While bias is unaffected by sample size, the variance of the estimator is a function of the number of plots and the underlying variability of the population. Benefits of large sample sizes are realized in the periodic design and for the rotating panel design when full implementation is near or complete. Designs such as the balanced annual partial remeasurement use smaller numbers of sample plots for estimation and generally have larger variances. Awareness of the design considerations and estimation results presented in this research may assist others develop a strategy to identify the best inventory design.

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APPENDIX

$$
\begin{bmatrix}
\bar{y}_1(2) \\ \bar{y}_1(8) \\ \bar{y}_7(3) \\ \bar{y}_2(3) \\ \bar{y}_2(8) \\ \bar{y}_{12}(4) \\ \bar{y}_8(4) \\ \bar{y}_3(4) \\ \bar{y}_3(8) \\ \bar{y}_{16}(5) \\ \bar{y}_{13}(5) \\ \bar{y}_9(5) \\ \bar{y}_4(5) \\ \bar{y}_4(8) \\ \bar{y}_{19}(6) \\ \bar{y}_{17}(6) \\ \bar{y}_{14}(6) \\ \bar{y}_{10}(6) \\ \bar{y}_5(6) \\ \bar{y}_5(8) \\ \bar{y}_{21}(7) \\ \bar{y}_{20}(7) \\ \bar{y}_{18}(7) \\ \bar{y}_{15}(7) \\ \bar{y}_{11}(7) \\ \bar{y}_6(7) \\ \bar{y}_6(8)
\end{bmatrix}
=
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\bar{Y}(2) \\ \bar{Y}(3) \\ \bar{Y}(4) \\ \bar{Y}(5) \\ \bar{Y}(6) \\ \bar{Y}(7) \\ \bar{Y}(8)
\end{bmatrix}
+
\begin{bmatrix}
e(\bar{y}_1(2)) \\ e(\bar{y}_1(8)) \\ e(\bar{y}_7(3)) \\ e(\bar{y}_2(3)) \\ e(\bar{y}_2(8)) \\ e(\bar{y}_{12}(4)) \\ e(\bar{y}_8(4)) \\ e(\bar{y}_3(4)) \\ e(\bar{y}_3(8)) \\ e(\bar{y}_{16}(5)) \\ e(\bar{y}_{13}(5)) \\ e(\bar{y}_9(5)) \\ e(\bar{y}_4(5)) \\ e(\bar{y}_4(8)) \\ e(\bar{y}_{19}(6)) \\ e(\bar{y}_{17}(6)) \\ e(\bar{y}_{14}(6)) \\ e(\bar{y}_{10}(6)) \\ e(\bar{y}_5(6)) \\ e(\bar{y}_5(8)) \\ e(\bar{y}_{21}(7)) \\ e(\bar{y}_{20}(7)) \\ e(\bar{y}_{18}(7)) \\ e(\bar{y}_{15}(7)) \\ e(\bar{y}_{11}(7)) \\ e(\bar{y}_6(7)) \\ e(\bar{y}_6(8))
\end{bmatrix}
$$

Appendix (1)

$$
\Sigma_4 =
\begin{bmatrix}
\sigma(\bar{y}_{12}(4), \bar{y}_{12}(4)) & 0 & 0 & 0 \\
0 & \sigma(\bar{y}_8(4), \bar{y}_8(4)) & 0 & 0 \\
0 & 0 & \sigma(\bar{y}_3(4), \bar{y}_3(4)) & \sigma(\bar{y}_3(4), \bar{y}_3(8)) \\
0 & 0 & \sigma(\bar{y}_3(8), \bar{y}_3(4)) & \sigma(\bar{y}_3(8), \bar{y}_3(8))
\end{bmatrix}
$$

Appendix (2)