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# Toward error analysis of large-scale forest carbon budgets

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## ABSTRACT

Quantification of forest carbon sources and sinks is an important part of national inventories of net greenhouse gas emissions. Several such forest carbon budgets have been constructed, but little effort has been made to analyse the sources of error and how these errors propagate to determine the overall uncertainty of projected carbon fluxes. We performed an error analysis for estimates of tree volume and volume change determined by repeated measurements of permanent sample plots for the South-eastern United States as a step toward assessing errors in the carbon budget constructed by the USDA Forest Service. Error components recognized were: sampling error for sample plot selection; measurement error for tree height and diameter; and regression error for tree volume. Most of the propagated error in volume and volume change estimation was due to sampling error. Error estimates depended on the size of the area examined (single state to region) and the degree to which tree growth and recruitment balanced mortality and harvesting. Approximate regional 95% confidence intervals were 3 455 073 000 ± 39 606 000 (1.1%) $m^3$ for current growing-stock volume, and 10 616 000 ± 4210 000 (39.7%) $m^3$ $years^{-1}$ for growing-stock volume change. These methods should be useful in further analysis of the sources of error and overall uncertainty in national efforts to quantify carbon fluxes associated with forests and land cover dynamics.

**Key words** Carbon budget, carbon flux, error analysis, forest, forest inventory, South-eastern USA, wood volume.

## INTRODUCTION

Rising atmospheric $CO_2$ concentrations are causing increasing concern about greenhouse gas-induced global climate change (Houghton *et al.*, 1995). While the majority of the increase is due to emissions from fossil fuel combustion, 20–25% is due to land use change (Houghton *et al.*, 1995). Due to their high carbon density relative to other ecosystems, forests play a particularly important role. Changes in the carbon standing stock of trees reflect the balance between growth and mortality (including harvesting) and determine the status of forests as an atmospheric carbon source or sink. The United Nations (UN) Framework Convention on Climate Change calls for nations to commit to the objective of providing national inventories of net greenhouse gas emissions, including carbon sources and sinks associated with forests and land cover change (Houghton *et al.*, 1997). Several such large-scale forest carbon budgets have been constructed (e.g. Kauppi *et al.*, 1992; Kurz *et al.*, 1992; Turner *et al.*, 1995), but little effort has been made to analyse the sources of error and how these errors propagate to determine the overall uncertainty of projected carbon fluxes.

Birdsey (1992) constructed a carbon budget for US forests based on the USDA Forest Service's Forest Inventory and Analysis program (FIA),

**Table 1** Description of FIA inventory sampling for the five South-eastern US states

| State | Florida | Georgia | North Carolina | South Carolina | Virginia | Total |
|---|---|---|---|---|---|---|
| Previous inventory year | 1987 | 1982 | 1984 | 1986 | 1986 | |
| Current inventory year | 1995 | 1989 | 1990 | 1993 | 1992 | |
| Timberland area (ha) | 5 929 122 | 9 563 552 | 7 572 091 | 5 040 508 | 6 251 623 | 34 356 897 |
| No. of remeasured sample plots | 5591 | 7329 | 5429 | 4453 | 4324 | 27 126 |
| No. of trees measured in current inventory | 87 970 | 133 302 | 127 503 | 91 294 | 95 716 | 535 785 |

which determines changes in tree wood volume by repeated measurements of permanent sample plots. Birdsey (1992) converted these wood volume stocks and changes to biomass and then to carbon content to construct a carbon budget, which addresses the need for estimates of US forest $CO_2$ sources or sinks. The purpose of our study was to identify and quantify the various sources of error involved in estimation of wood volume and volume changes following the FIA methodology, and using the south-eastern United States as an example. This provides a first step toward a complete error analysis of a national level forest carbon budget, such as that produced by Birdsey (1992). It should also be applicable to other countries estimating carbon fluxes by the 'stock-change method' (Winjum *et al.*, 1998), which utilizes repeated inventories to estimate changes in carbon pool sizes over time.

## MATERIALS AND METHODS

We desired a large region with repeated inventory data available as a test case to demonstrate our methods of error analysis. The five states in the South-eastern FIA unit (Virginia, North Carolina, South Carolina, Georgia, Florida) were selected as our study area. We examined current inventory wood volume and volume changes between inventories within timberland (land capable of producing 1.4 $m^3$ of industrial wood per ha per year) for the five states. Wood volume was measured as growing-stock volume, defined as wood volume of trees $> 12.7$ cm (diameter at breast height (d.b.h.) –1.37 m), from a 30.5-cm high stump to a minimum 10.2-cm top diameter on the central stem; wood in branches to a minimum 10.2-cm diameter is included (Brown, 1996). The South-eastern FIA unit uses a two-stage sampling scheme in locating permanent sampling points (Birdsey & Schreuder, 1992). The second stage involves random selection of sample points from a systematic grid that was located from a random starting point. All sample points measured in the most recent inventory for each state were used to estimate current growing-stock volume. Those sample points that were remeasured from the previous inventory were used to estimate growth, mortality, removals (harvested trees) and net growing-stock volume change (Table 1).

In the South-eastern FIA unit, at each sampling point, all trees between 2.5 and 12.7 cm d.b.h. within a circular plot of radius 2.07 m were included in the sample. Point sampling with a 37.5 basal area factor (BAF) prism was used to determine which trees $\geq 12.7$ cm d.b.h. were included in the sample (Birdsey & Schreuder, 1992). (This is an optical method which includes trees whose diameter subtends at least a specified threshold angle when viewed from a fixed point; this essentially establishes variable radius plots for trees of different sizes.) D.b.h. was measured for each tree sampled. Tree height was measured for 20% of the trees and estimated for the other 80% by visual comparison with the measured trees. Growing-stock volume was estimated for each tree by regression with $[DBH^2 \times height]$. These regression equations have been developed from detailed measurements made on > 40 000 standing and felled sample trees (Birdsey & Schreuder, 1992). The current growing-stock volume ($V_i$), removal volume ($R_i$) and net growth volume ($N_i$ = gross growth $[G_i]$ — natural mortality $[M_i]$), were computed as appropriate for each tree. In the FIA, these volumes were multiplied by the appropriate area expansion factors ($f_i$) and summed over individuals ($i$) and states ($j$) to give regional estimates of growing-stock current volume, e.g.

$$V = \sum_j \sum_i f_{ij} V_{ij} \tag{1}$$

with similar equations for removals ($R$) and net growth ($N$). Net growth minus removals represents the net change in growing-stock volume between inventories ($\Delta V$). (Area expansion factors represent the inverse of sampling intensity, and are used to scale sampled tree volumes up to volume/acre and total volume over an area.)

Following Cunia's (1965) scheme, we recognized three sources of error for estimation of growing-stock volume and volume changes: sampling error, measurement error (for both d.b.h. and height) and regression error. We examined in detail the methods for sampling, regression, and measurement in order to quantify the errors in each of these processes, and calculated how these errors propagate.

## Sampling error

Sampling error reflects the variability in the estimate due to measuring only a subset of the population of interest. Sampling standard errors have been computed by the USDA Forest Service, taking into account the sampling design and sample intensity for each state's inventory and including error in area measurement and expansion factors. The percent sampling standard errors for state totals of growing-stock volume, net growth (gross growth — mortality), and removals were taken from the states' inventory reports (Thompson, 1989; Brown, 1993, 1996; Conner, 1993; Thompson & Johnson, 1994). The percent sampling standard errors times the corresponding estimates for volume, net growth and removals represent 1 sampling standard error (SE) of these estimates. Squaring these sampling standard errors gives the sampling variances for state $j$ for volume ($\sigma_{V_j,s}{}^2$), net growth ($\sigma_{N_j,s}{}^2$) and removals ($\sigma_{R_j,s}{}^2$). Total sampling variances for volume ($\sigma_{V,s}{}^2$), net growth ($\sigma_{N,s}{}^2$) and removals ($\sigma_{R,s}{}^2$) for the five state regions were computed as the sum of the state sampling variances, assuming independent sampling errors (since the sampling is independent among states), e.g.

$$\sigma^2_{V,s} = \sum_j \sigma^2_{V_j,s} \tag{2}$$

The equations for net growth ($s_{N,s}{}^2$), and removals ($s_{R,s}{}^2$) followed this same form.

## Regression error

Calculations of growing-stock volume for the FIA unit were made by regression equations with [DBH$^2$ × height] as the independent variable (Birdsey & Schreuder, 1992). Since the exact equations used varied by species and physiographic province, and were not provided in the Eastwide Forest Inventory Data Base (USDA Forest Service, 1998), equations for loblolly pine (*Pinus taeda* L.) and white oak (*Quercus alba* L.) from McClure *et al.* (1983) were taken to be representative for softwood and hardwood species, respectively. Examination of available regression statistics for several other tree species verified the similarity of regression standard errors among softwood species (Clark & Saucier, 1990) and among hardwood species (Clark *et al.*, 1986). Regression data included 5134 loblolly pine trees ranging from 0 to 10 m$^3$ growing-stock volume, and 1484 white oak trees ranging from 0 to 6 m$^3$ growing-stock volume. Individual prediction error variances for current growing-stock volume ($\sigma_{V_{ij},r}{}^2$), mortality ($\sigma_{M_{ij},r}{}^2$) and removals ($\sigma_{R_{ij},r}{}^2$) by three d.b.h. classes of softwoods and hardwoods were computed from regression statistics given in McClure *et al.* (1983).

The area expansion factor, $f_{ij}$, is a constant which scales the contribution of an individual sample tree $i$ in state $j$ to the total volume estimate of an area. Since $f_{ij}$ is a constant, then the prediction variance of the area expanded volume estimate ($\sigma_{f_{ij}V_{ij},r}{}^2$) can be rewritten as:

$$\sigma^2_{f_{ij}V_{ij},r} = f_{ij}^2 \sigma^2_{V_{ij},r} \tag{3}$$

Assuming the independence of regression errors of individual trees and states, then the regional regression error variance for the area expanded total growing-stock volume over $i$ individuals and $j$ states from Eqn 1 is:

$$\sigma^2_{V,r} = \sum_j \sum_i \sigma^2_{f_{ij}V_{ij},r} = \sum_j \sum_i f_{ij}^2 \sigma^2_{V_{ij},r} \tag{4}$$

where the rightmost term has been rewritten as in Eqn 3. The equations for regression error variance for removals ($\sigma_{R,r}{}^2$) and mortality ($\sigma_{M,r}{}^2$) were similar, where the d.b.h. classes refer to the d.b.h. at the time of removal or mortality, as provided in the FIA database.

The portion of growing-stock volume attributable to individual tree growth since the last inventory is calculated in the FIA by subtraction of the previous volume (based on previous d.b.h. and height) from the current volume (based on current d.b.h. and height). Regression error variances for previous volume ($V_{0ij}$) and current volume ($V_{ij}$) were computed for each individual tree as outlined above. A first-order Taylor series approximation for the error variance of growth ($G_{ij}$) as the difference of two non-independent variables, $V_{ij}$ and $V_{0ij}$ may be written as (Taylor 1997):

$$\begin{aligned}\sigma^2_{G_{ij},r} &= \sigma^2_{V_{ij},r} + \sigma^2_{V_{0ij},r} - 2\sigma_{V_{ij},r V_{0ij},r} \\ &= \sigma^2_{V_{ij},r} + \sigma^2_{V_{0ij},r} - 2\rho\sigma_{V_{ij},r}\sigma_{V_{0ij},r} \qquad (5)\end{aligned}$$

where ρ is the correlation between the regression errors of $V_{ij}$ and $V_{0ij}$. Errors in volume estimation at two times for a given tree are unlikely to be independent of each other. For example, the volume for a tree with an unusual growth form may be underestimated in the first inventory. If the growth form is still unusual at the time of the next inventory, volume will probably be underestimated again. Thus, the errors are expected to be positively correlated, and higher correlations lead to lower values of error variance for $\sigma_{G_{ij},r}{}^2$. Since no data were available to estimate this correlation, we used what we judged to be a conservative (low) estimate of 0.5. To the extent that this estimate of error correlation is low, this will lead to erring on the high side for the estimate of regression error variance for growth, $\sigma_{G_{ij},r}{}^2$.

## Measurement error

Measurement error precision for d.b.h. was ± 2.5 mm (±0.1 inch) for trees less than 25.4 cm (10 inches) d.b.h., and ±5 mm (±0.2 inch) for trees of 25.4 cm d.b.h. or greater (USDA Forest Service, 1991). Taking this precision to be ±2 standard deviations (SD) gives measurement error SD's ($\sigma_{D_{ij}}$) of ±1.3 mm and ±2.5 mm for the two size classes. The precision of height estimation was < ±10% for 80% of the measurements (USDA Forest Service, 1991). Assuming that the height errors are normally distributed, an 80% confidence interval corresponds to 1.282 SD, and the coefficient of variation ($C_{H_{ij}} = \sigma_{H_{ij}}/H_{ij}$) of height measurement error was taken to be 7.8% (= 10%/1.282). Repetition of 5% of the d.b.h. and height measurements in each inventory unit for quality assurance validated these estimates of measurement error values (Noel Cost, pers. comm.).

Utilizing a first-order Taylor series expansion for a function $q = f(x,y)$, the variance of $q$ can be expressed as (Taylor 1997):

$$\sigma^2_{ij} = \left(\frac{\partial q}{\partial x}\right)^2 \sigma^2_x + \left(\frac{\partial q}{\partial y}\right)^2 \sigma^2_y + 2\frac{\partial q}{\partial x}\frac{\partial q}{\partial y}\sigma_{x,y} \qquad (6)$$

The last term is a covariance term, which drops out if the measurements of $x$ and $y$ are independent. Assuming independence of the measurement errors for height ($H$) and d.b.h. ($D$), and applying this equation to the volume ($V$) regression function $V_{ij} = a + bD_{ij}{}^2H_{ij}$, gives an estimate of the variance in volume as a result of measurement errors in height and d.b.h. for an individual tree $i$ in state $j$:

$$\sigma^2_{V_{ij},m} = (2bD_{ij}H_{ij}\sigma_{D_{ij}})^2 + (bD^2_{ij}\sigma_{D_{ij}})^2 \qquad (7)$$

This can be rewritten in terms of the coefficients of variation for the d.b.h. ($C_{D_{ij}} = \sigma_{D_{ij}}/D_{ij}$) and height ($C_{H_{ij}} = \sigma_{H_{ij}}/H_{ij}$) measurements:

$$\begin{aligned}\sigma^2_{V_{ij},m} &= \left(2bD^2_{ij}H\frac{\sigma_{D_{ij}}}{D_{ij}}\right)^2 + \left(bD^2_{ij}H\frac{\sigma_{H_{ij}}}{H_{ij}}\right)^2 \\ &= (2bD^2_{ij}H_{ij}C_{D_{ij}})^2 + (bD^2_{ij}H_{ij}C_{H_{ij}})^2 \qquad (8)\end{aligned}$$

Since the regression equation $V_{ij} = a + bD_{ij}{}^2H_{ij}$ has a negligible intercept $a$ (McClure *et al.*, 1983), then $V_{ij} \approx bD_{ij}{}^2H_{ij}$ and Eqn 6 can be approximated as:

$$\sigma^2_{V_{ij},m} \approx (2V_{ij}C_{D_{ij}})^2 + (V_{ij}C_{H_{ij}})^2 \qquad (9)$$

The two terms on the right-hand side represent the variance in the volume estimate for tree $i$ in state $j$ due to measurement error in d.b.h. ($\sigma_{V_{ij},D_{ij}}{}^2$) and height ($\sigma_{V_{ij},H_{ij}}{}^2$), respectively.

Once again, if we assume independence of measurement errors for individual trees, then the variance due to measurement error of the growing-stock volume expanded to the entire study area is:

$$\sigma^2_{V,m} = \sum_j \sum_i f^2_{ij} \sigma^2_{V_{ij},m}$$

$$= \sum_j \sum_i f^2_{ij} (\sigma^2_{V_{ij},D_{ij}} + \sigma^2_{V_{ij},H_{ij}}) \qquad (10)$$

Similar equations were used for the variances for removals ($\sigma_{R,m}{}^2$) and net growth ($\sigma_{N,m}{}^2$).

### Total error

Following the approach of Gertner (1990), the variance in the total regional growing-stock volume accounting for all the sources of error is:

$$\sigma^2_V = \sigma^2_{V,s} + \sigma^2_{V,r} + \sigma^2_{V,m}$$

$$= \sigma^2_{V,s} + \sigma^2_{V,r} + \sigma^2_{V,D} + \sigma^2_{V,H} \qquad (11)$$

and similarly for net growth ($\sigma_{N,s}{}^2$) and removals ($\sigma_{R,s}{}^2$). Because growing-stock volume change since the last inventory is the difference between net growth and removals ($\Delta V = G - R$), the variance for volume change was computed as:

$$\sigma^2_{\Delta V} = \sigma^2_G + \sigma^2_R \qquad (12)$$

assuming independence of the net growth and removal estimates. This is a reasonable assumption because the estimates are based on different individual trees.

## RESULTS AND DISCUSSION

The sampling, regression and measurement error variances for wood volume, net growth, removals and net volume change were computed for each state and the entire region as outlined above. Table 2 presents these results as standard errors (square roots of variances) for each of these sources of error, so that their magnitudes may be compared directly with the volume estimates. The coefficients of variation (CV = 100% × SE/volume estimate) are also presented to aid these comparisons. Finally, Table 2 indicates how the total error variance was partitioned among the various sources of error for each estimate.

### Sampling error

For growing-stock volume, the sampling error CV's ranged from 1.13% to 1.65% for individual states (Table 2). As state estimates are aggregated into a regional estimate, the percentage sampling error decreases because both the total volume and the variance increase additively, but the SE increases only as the square root of the variance. Consequently, the sampling error CV was only 0.57% for the five-state total growing-stock volume. Similarly, state sampling errors varied from 1.17 to 4.14% for net growth, and 2.58–4.65% for removals, with regional sampling errors of 0.76% and 1.57%, respectively.

The South-eastern FIA unit of the USDA Forest Service targets a sampling error of 5% per $28.3 \times 10^6$ m$^3$ (one billion ft$^3$) growing-stock volume in designing their sampling scheme (Noel Cost, pers. comm.). As a rough approximation, sampling error may be expected to change inversely proportional to the square root of the volume considered (Thompson, 1989; Brown, 1993, 1996; Thompson & Johnson, 1994; Conner, 1993). The total growing-stock volume for the South-east is two orders of magnitude larger than the target volume of 1 billion ft$^3$, and the sampling error is correspondingly one order of magnitude smaller than the design level of 5% (Table 2). Thus, this estimate of sampling error (0.57%) for the growing-stock volume of the region appears reasonable.

### Regression error

While the regression error variances for individual trees were not negligible (McClure *et al.*, 1983), the very large $n$ (> 500 000 trees inventoried, Table 1) made the standard errors small in comparison to the volume estimates (Table 2). This was true for estimates of current growing-stock volume, as well as for net growth and removals. However, because volume change represents the difference between net growth and removals, it is a considerably smaller value and the regression standard error accounted for a larger percentage of the regional estimate (Table 2). For Georgia, where net growth and removals nearly balanced each other, there was a small decrease in growing-stock volume between inventories of $762 \times 10^3$ m$^3$ years$^{-1}$, and the regression error of

**Table 2** Error components and total error (SE = standard error) for estimates of growing-stock volume (GSV) from the latest state inventory, and growing-stock volume change between inventories (growth — mortality — removals). CV is coefficient of variation = 100% × standard error/mean. The rightmost column gives the percentage of variance in the estimate which is due to each error source

| | Florida | Georgia | North Carolina | South Carolina | Virginia | Total | Total CV (%) | % of total variance |
|---|---|---|---|---|---|---|---|---|
| Growing-stock volume ($10^3$ m$^3$) | 435 129 | 870 288 | 927 160 | 472 473 | 750 023 | 3 455 073 | | |
| % sampling error | 1.65 | 1.16 | 1.13 | 1.51 | 1.14 | | | |
| SE: Sampling | 7180 | 10 095 | 10 477 | 7134 | 8550 | 19 678 | 0.57 | 98.7% |
| SE: Regression | 650 | 1080 | 1117 | 715 | 1086 | 2128 | 0.06 | 1.2% |
| SE: Measurement — d.b.h. | 34 | 57 | 58 | 38 | 54 | 110 | 0.00 | 0.0% |
| SE: Measurement — height | 191 | 317 | 337 | 219 | 311 | 629 | 0.02 | 0.1% |
| SE: total | 7212 | 10 158 | 10 542 | 7174 | 8625 | 19 803 | 0.57 | 100.0% |
| GSV net growth ($10^3$ m$^3$/yr) | 19 652 | 36 094 | 32 836 | 14 877 | 24 024 | 127 483 | | |
| % sampling error | 1.72 | 1.17 | 1.23 | 4.14 | 1.29 | | | |
| SE: Sampling | 338 | 422 | 404 | 616 | 310 | 965 | 0.76 | 89.6% |
| SE: Regression | 97 | 156 | 172 | 118 | 173 | 327 | 0.26 | 10.3% |
| SE: Measurement — d.b.h. | 3 | 4 | 3 | 3 | 3 | 7 | 0.01 | 0.0% |
| SE: Measurement — height | 14 | 16 | 14 | 19 | 12 | 35 | 0.03 | 0.1% |
| SE: total | 352 | 451 | 439 | 627 | 355 | 1020 | 0.80 | 100.0% |
| GSV removals ($10^3$ m$^3$/yr) | 15 856 | 36 856 | 26 596 | 20 602 | 16 957 | 116 867 | | |
| % sampling error | 3.59 | 2.58 | 3.68 | 3.63 | 4.65 | | | |
| SE: Sampling | 569 | 951 | 979 | 748 | 789 | 1835 | 1.57 | 99.2% |
| SE: Regression | 50 | 87 | 77 | 59 | 63 | 153 | 0.13 | 0.7% |
| SE: Measurement — d.b.h. | 3 | 5 | 4 | 3 | 3 | 8 | 0.01 | 0.0% |
| SE: Measurement — height | 14 | 26 | 24 | 19 | 19 | 47 | 0.04 | 0.1% |
| SE: total | 572 | 955 | 982 | 750 | 791 | 1842 | 1.58 | 100.0% |
| GSV change ($10^3$ m$^3$/yr) | 3797 | −762 | 6240 | −5725 | 7067 | 10 616 | | |
| SE: Sampling | 662 | 1040 | 1059 | 969 | 847 | 2073 | 19.53 | 97.0% |
| SE: Regression | 109 | 179 | 188 | 132 | 184 | 361 | 3.40 | 2.9% |
| SE: Measurement — d.b.h. | 4 | 6 | 5 | 5 | 4 | 11 | 0.10 | 0.0% |
| SE: Measurement — height | 20 | 31 | 28 | 27 | 23 | 58 | 0.55 | 0.1% |
| SE: total | 671 | 1056 | 1076 | 978 | 867 | 2105 | 19.83 | 100.0% |

$179 \times 10^3$ m$^3$ years$^{-1}$ amounted to 23% of the volume change estimate.

## Measurement error

Measurement tolerances for d.b.h. were very tight (±2.5 mm or ±5mm) and thus did not contribute materially to the variance in any of the volume estimates (Table 2). While individual tree height measurements were considerably more variable (CV of 7.8%), the very large number of trees inventoried decreased the height measurement standard errors to small values (regional CVs less than 1% for all volume, growth, removal, and change estimates). For individual states, height measurement error at its greatest led to a CV of 4% for Georgia, with its rough balance of net growth and removals as discussed above.

## Total error

Total standard errors ranged from 1 to 2% of the growing-stock volume estimates for the individual states (Table 2). When the state volume estimates were aggregated to the region, the total standard error was a modest 0.57%. An approximate 95% confidence interval (mean ±2 SE) for regional current growing-stock volume is $3455\,073 \pm 39\,606 \times 10^3$ m$^3$ ($122\,015 \pm 1397 \times 10^6$ ft$^3$). Total errors for net growth and removals were somewhat higher with regional estimate standard errors of 0.8% and 1.58%, respectively, and approximate 95% confidence intervals of 127 483 ± 2040 × $10^3$ $m^3$ (4502 ± 72 × $10^6$ $ft^3$) and 116 867 ± 3684 × $10^3$ $m^3$ (4127 ± 130 × $10^6$ $ft^3$). The total standard error for volume change, however, approached 20% for the regional estimate, and ranged from 12% (Virginia) to 139% (Georgia) for the individual states. An approximate 95% confidence interval for regional growing-stock volume change is 10 616 ± 4210 × $10^3$ $m^3$ $years^{-1}$ (375 ± 149 × $10^6$ $ft^3$ $years^{-1}$). This volume-change confidence interval is so wide (~ ±40%) because of the near cancellation of changes from net growth and removals. Preliminary analyses of similar data from the prior inventories for these states showed similar total standard errors, but a fourfold increase in volume change, resulting in a fourfold smaller 95% confidence interval of ~ ±10% (Phillips *et al.*, 1998).

Total error was dominated by sampling error in all instances. For regional estimates of volume, net growth, removals and volume change, sampling error accounted for 90–99% of the variance. The next largest component was regression error, followed by measurement error for height, and lastly measurement error for d.b.h. For a red pine stand in Michigan, Gertner (1990) similarly found that sampling error accounted for 93% of the total variance.

It should be noted that only random variation, and not systematic bias, were considered in the measurement of d.b.h. and height. Gertner (1990) found that volume estimates for a red pine stand were very sensitive to systematic biases of 5–25% in the measurement of d.b.h. These are very large biases indeed, well beyond the bounds of the stated precision of the d.b.h. measurements for our study area, with SEs in the order of 1–2% (USDA Forest Service, 1991). Height measurements were of somewhat lower precision, but rechecking of 5% of the d.b.h. and height measurements throughout the South-east bore out the precision estimates and did not indicate that there was any substantial systematic bias in the measurements (Noel Cost, pers. comm.).

Construction of symmetrical confidence intervals for current volume or volume change estimates (e.g. mean ±2 SE for ~95% confidence interval) from the results in Table 2 assumes that the total error is normally distributed. Since total error is determined by multiple additive sources of error, this might be expected by the Central Limit Theorem even if the component sources of error were not normally distributed. However, the assumption of normality may also be justified for component error sources. The USDA Forest Service computes sampling standard errors for each state based on the sampling design and sampling intensity, and provides formulas for estimating standard errors and normal distribution confidence intervals for subsets of the state (Thompson, 1989; Brown, 1993, 1996; Thompson & Johnson, 1994; Conner, 1993). McClure *et al.* (1983) examined and confirmed the assumption of normality for volume within each tree size class, indicating normally distributed regression errors. While there are no explicit data available on the distribution of measurement errors for tree diameter and height beyond statements of precision limits, the contribution of these error sources was minimal (Table 2) and non-normality would not be likely to make any measurable difference in the total error estimate.

## CONCLUSIONS

A detailed accounting of sources of error in the estimation of current growing-stock volume as well as net growth (gross growth — mortality), removals and growing-stock volume change between FIA inventories for the south-eastern US revealed the following features:

**1** Approximate 95% confidence intervals (mean ±2 SE) for the South-east, as of the latest available state inventories, were:

- 3455 073 ± 39 606 × $10^3$ $m^3$ (122 015 ± 1397 × $10^6$ $ft^3$) for current growing-stock volume;
- 127 483 ± 2040 × $10^3$ $m^3$ (4502 ± 72 × $10^6$ $ft^3$) for net growth;
- 116 867 ± 3684 × $10^3$ $m^3$ (4127 ± 130 × $10^6$ $ft^3$) for removals;
- and 10 616 ± 4210 × $10^3$ $m^3$ $years^{-1}$ (375 ± 149 × $10^6$ $ft^3$ $years^{-1}$) for growing-stock volume change.

**2** Total error was dominated by sampling error, with random measurement and regression errors greatly diminished due to the large number of individual trees inventoried.

**3** CVs for various error components were larger for estimates of net growth and removals than for current volume because they: (a) involved only a subset of the total number of trees; (b) represented compounding of errors in two inventories, and; (c) represented percentages of a much smaller estimate. This was even more the case for growing-stock volume change, because the estimate was even smaller, representing the difference between net growth and removals between successive inventories.

**4** Similarly, error CVs were much larger for individual states in which net growth and removals were most closely balanced.

This study represents an initial step in developing an error budget for large-scale (e.g. national) assessments of forest carbon sources and sinks, as called for by the UN Framework Convention on Climate Change (Houghton *et al.*, 1997). One example is the forest carbon budget for the United States developed by Birdsey (1992), which used repeated inventories from the USDA Forest Service's FIA system. Subsequent steps toward a carbon source/sink error budget for trees will need to move from wood volume to biomass and carbon content. We are examining four alternative procedures for this:

(a) Convert from growing-stock wood volume to total biomass on an individual tree basis.

(b) Develop a relationship between total biomass of all trees and growing-stock volume in a stand (Schroeder *et al.*, 1997; Brown & Schroeder, 1999), which varies with stand volume.

(c) Apply generic hardwood and softwood biomass equations based on d.b.h. instead of volume equations (Schroeder *et al.*, 1997).

(d) Apply species-specific biomass equations based on d.b.h. instead of volume equations (e.g. Clark *et al.*, 1986).

Additional efforts will be required to examine tree below-ground parts and other components, such as coarse woody debris, understorey biomass and soil carbon, for a more complete forest carbon budget.

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