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Forest Inventory-Based Estimation of Carbon Stocks and Flux in California Forests in 1990

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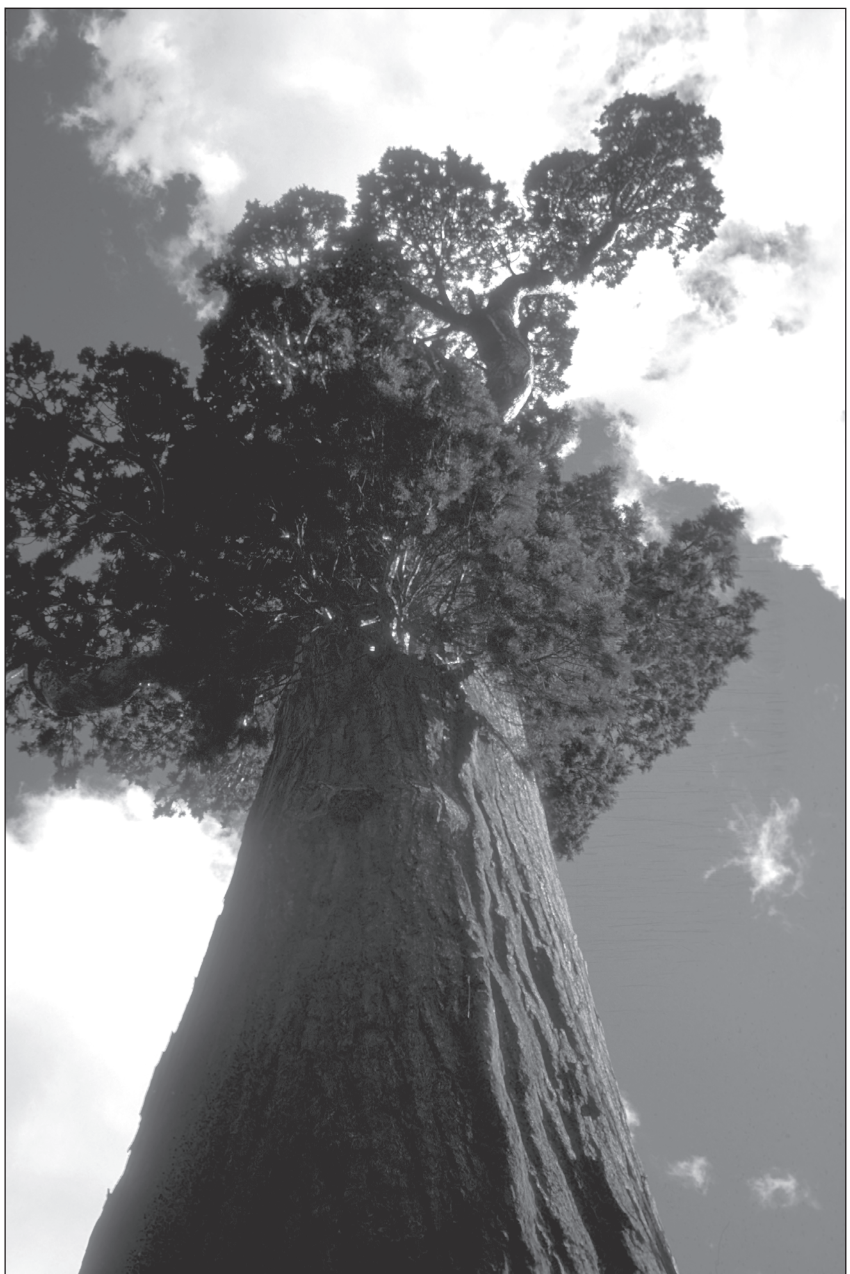

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Abstract

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Estimates of forest carbon stores and flux for California circa 1990 were modeled from forest inventory data in support of California's legislatively mandated greenhouse gas inventory. Reliable estimates of live-tree carbon stores and flux on timberlands outside of national forest could be calculated from periodic inventory data collected in the 1980s and 1990s; however, estimation of circa 1990 flux on national forests and forests other than timberland was problematic owing to a combination of changing inventory protocols and definitions and the lack of remeasurement data on those land categories. We estimate annual carbon flux on the 7.97 million acres of timberlands outside of national forests (which account for 24 percent of California's forest area and 28 percent of its live tree aboveground biomass) at 2.9 terragrams per year.

Keywords: Forest carbon flux assessment, biomass, carbon stocks, carbon dioxide, Forest Inventory and Analysis.

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Introduction

The U.S. Department of Agriculture, Forest Service (USFS), Pacific Northwest Research Station, Forest Inventory and Analysis Program (PNW-FIA) was asked on October 15, 2007, by the USFS Pacific Southwest (Region 5) and Pacific Southwest Research Station to prepare an estimate of circa 1990 carbon stocks and stock change (often referenced hereafter as flux[1]) in California forests by November 1, 2007. This was to be done in support of greenhouse gas inventory efforts by the state of California pursuant to Assembly Bill 32 ("AB 32"), also known as the "Global Warming Solutions Act of 2006, a state law that mandates a return to 1990 greenhouse gas emissions by 2020, with further reductions in emissions thereafter. The California Air Resources Board has been engaged in creating a greenhouse gas inventory for every sector of the state's economy. As perhaps the only sector with the potential for negative net emissions (i.e., sequestration of carbon in standing trees, long-lived forest products, and as biomass-generated energy that substitutes for fossil fuel-generated energy), forestry is a particularly important sector in this accounting effort.

In addition to the sector-wide and owner-class-specific tracking of sequestration of carbon in forest biomass, key questions concerning greenhouse gases and climate change will depend on the georeferenced network of over 6,800 forested PNW-FIA plots in California. The occurrence of fire, insect, and disease events is dependent on both land ownership and location with respect to stressors. In addition to changing the carbon flux, these events can have substantial impacts on other greenhouse gas emissions such as methane, nitrous oxide, biogenic hydrocarbons, and the precursors to tropospheric ozone. Most of the current data on these relationships are forest-type-specific, and therefore cannot be used for statewide accounting without spatially accurate products (e.g., Cahill et al. 2006). In addition, spatially accurate information on forest cover will be crucial in tracking albedo impacts of changes such as the extent of the pinyon-juniper coverage in arid parts of the state. Although albedo is not directly related to greenhouse gas emission, reductions in albedo from the replacement of grasslands with forests or woodlands can have major impacts on the rate of radiative forcing, the driving force of climate change (Solomon et al. 2007).

[1] We us the term "flux" synonymously with "stock change" such that positive values of flux indicate sequestration of atmospheric carbon by the forest pool and negative values suggest emissions from the forest pool into the atmosphere. This is opposite of how some of the carbon literature defines flux, where positive numbers indicate emissions into the atmosphere, so when comparing flux estimates in this report with such literature, it is important to remember to reverse the sign.

Earlier, model-based efforts to characterize carbon stocks and fluxes in the five major forest pools (live aboveground, live belowground, dead [standing and down], litter, and soil organic carbon) did not successfully develop plausible estimates, and concerns about the estimates were registered with the California Air Resources Board by various state and federal agencies. The PNW-FIA Program was asked to complete a scientifically grounded analysis that will ensure valid estimates, or at least the best possible estimates producible on this highly compressed timeline. Given the state of the data available, there is no one correct answer or approach; scientists at PNW-FIA have undertaken a convergence-of-evidence approach—in essence, following multiple pathways to generate the requisite estimates, and documenting the logic, attendant uncertainties, caveats, and issues that must be considered when interpreting these estimates. In addition to the development of a statistically supportable baseline for the state and for different ownerships, the spatially georeferenced, plot-based approach will allow for future integration of data from new plot-based information, forest-type-specific releases of other greenhouse gases, as well as changes in forest cover. This report presents the estimates and supporting logic.

Data Sources

Because this application requires estimation of change in carbon stocks as a proxy for carbon flux (the primary attribute of interest), it is essential to perform calculations on comparable inventories, and ideally, on a remeasurement inventory in which the same plots and trees are measured with essentially the same protocols several years apart. Regrettably, for the year of interest (1990), consistent comparable inventories are lacking for most classes of forest land ownerships, productivity, and reserve status. A genuine, remeasurement inventory exists only for unreserved timberlands (as defined in the 1994 periodic inventory) outside of national forests (ONF). This land base, which was sampled in 1981–1984 (nominal 1984) and again in 1991-1994 (nominal 1994), comprises 24 percent of California's forest area and 28 percent of its live tree aboveground biomass. Because the remeasurement interval spans 1990, it is possible to estimate both carbon stocks and (average) flux for this base year for this land base. Unfortunately, this land base is not reflective of the other forest owner class/productivity class/reserved class combinations, so findings from the remeasurement analysis of ONF timberland cannot be extrapolated.

Comparing inventories with different designs and plot footprints is very challenging. Sampling errors are inherently higher, such that identifying significant differences becomes far more problematic (the differences must be much greater before they can be interpreted as statistically significant, and not just random artifacts of sampling error). The equation for the sampling error of the difference between two inventories is:

$$SE = \sqrt{\sigma_1^2 + \sigma_2^2 - 2CoVar_{1,2}} \quad (1)$$

where

$\sigma_1^2 =$ variance of the total (carbon, biomass, or any other inventory attribute) from inventory 1,

$\sigma_2^2 =$ variance of the total (carbon, biomass, or any other inventory attribute) from inventory 2, and

$CoVar_{1,2}$ = covariance between the two inventories.

For a complete remeasure (e.g., same footprint and trees), the covariance term can be quite large, such that the sampling error is greatly reduced below the square root of the sum of the variances of each inventory. When the inventories are completely independent (i.e., there is no connection between the samples for inventory 1 and inventory 2), the covariance term is zero and sampling error is maximized.

An even more daunting challenge results from the fact that the available inventories sample different forest owner class/productivity class/reserved class combinations, and have numerous instances of differences in definitions of, for example, forest land, timberland, ownership class, and reserve class, among others. We chose to use only inventory data structured as a systematic sample of California's forest with approximately uniform sampling intensity. A strata-based inventory was conducted on unreserved National Forest System (NFS) timberlands in the 1980s, although a tree-level data set derived from this inventory is not, to our knowledge, publicly available. Moreover, we believe that it would be difficult, if not impossible, to arrive at valid estimates of flux when comparing a strata-based inventory[2] and a (systematic) grid inventory such as those undertaken post-1990. This is especially true given that it is not even clear that the stratification layers used in this pre-1990 inventory exist today.

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[2] An inventory in which the total forest area is subdivided into strata, each believed to be relatively homogeneous and delineated in a georeferenced database, and sample plots are allocated to each stratum. Area expansion factors are developed as the quotient of stratum area and plot count, although plot density (and thus also area expansion factors) may differ greatly among strata.

The earliest available grid inventories for NFS lands and ONF "other forest" (forests that do not qualify as timberland owing to lower productivity) is post-1990, so estimation of 1990 stocks and flux becomes enormously problematic and necessitates what some might justifiably regard as "heroic" assumptions. The available inventories that meet these most minimal criteria (systematic grid inventory) and some relevant attributes are listed in table 1.

The National Information Management System (NIMS) refers to the annual FIA inventory of all forest lands (table 1). Each of these databases is a tree-level database, meaning that live-tree carbon can be calculated at the individual tree level, then expanded to account for the sample's representation in the landscape. The plots are divided into 10 interpenetrating (systematically spread out across the entire state) "panels" of approximately equal size, and in California, all the plots in one panel (10 percent of the total plots) are typically visited and assessed in the field in a given year.

The Integrated Database (IDB) is the first comprehensive database that brought together all the available forest inventories across ownerships (NFS and ONF) for California, Oregon, and Washington. It attempted to provide consistency in the data definitions, units of measure, expansion factors, and other inventory attributes to the extent possible so that analyses could be conducted across ownerships. However, there are fundamental differences among the inventories combined into this database that have inescapable implications for analysis. For example, the IDB database contains data collected in special studies on ONF, unreserved lands that are

Table 1—Available inventories and their attributes for California

Database	Remeasurement	Dates of collection	NFS[a]	NFS reserved	Other forest	Reserved areas (ONF)[b]	Timberland
NIMS[c]	No	2001–2006	Yes	Yes	Yes	Yes	Yes
IDB[d]	No	1991–1994 ONF 1993–2000 NFS	Yes	Yes	Partial	No	Yes
94_CA_Change[e]	Yes	1981–1983 and 1991–1994	No	No	Partial	No	Yes

[a] NFS = National Forest System.
[b] ONF = outside of national forest.
[c] NIMS = National Information Management System; data are available online (USDA Forest Service 2007).
[d] IDB = Integrated Database assembled by the PNW-FIA; data are available on CD (Waddell and Hiserote 2005).
[e] 94_CA_Change refers to the 1984-1994 change database.

not timberland (e.g., a sparse sample of oak woodland), but not **all** other forest (e.g., pinyon-juniper was not sampled). Inventory dates range from 1991 to 1994 for ONF plots, but data were collected one survey unit[3] at a time over that period (i.e., not a sample spread across the whole state each year as is done today under annual inventory). It also contains data collected on the national forests of Region 5 between 1993 and 2000, with national forests being sampled one at a time, moving mainly from north to south. However, the underlying designs of the ONF and NFS inventories differ, as do some of the key definitions, and both differ from the design and definitions of the annual inventory, NIMS. For example, some of the differences between periodic (IDB) and annual data pertinent to this analysis are:

- The annual inventory uses a different plot design (fixed plot with four subplots) than that used by the periodic inventories (variable-radius plot with five subplots), and only subplot one is co-located.
- The annual inventory samples all lands, whereas some of the periodic inventories did not sample certain lands such as state and national parks or unproductive forest land (other forest). Although this land area was accounted for in the periodic inventory, the volume on these unsampled lands was always unknown and implicitly characterized in the database as zero (i.e., the IDB has "proxy plot" records in its plot table to account for forested area within unsampled areas such as national parks, but no corresponding tree records in the tree table from which volume could be calculated).
- Plot stockability factors and stockable proportions were applied to different sets of plots in the periodic and annual inventories. Because stockability influences the level of productivity of a plot and whether or not it is classified as timberland, this may account for some differences in timberland area and volume between the two inventories.
- Area that was classified and sampled as oak woodlands (by virtue of the species present) during the periodic inventory represented in the IDB was, in some cases, classified as timberland in the annual inventory.

[3] California is partitioned into six, multicounty survey units for reporting inventory results: North Coast, Northern Interior, Sacramento, San Joaquin, Southern, and Central Coast. Prior to initiating annual inventories in 2001, inventory data collection was completed in one survey unit before moving on to the next such that collection dates for a given survey unit typically spanned no more than a year.

- To standardize the annual inventory across all lands nationally, there were differences (from the data contained in IDB) in definitions and protocols for what is considered a tree, forest land, reserved land, and timberland.

Each of these databases covers a different land base and presents different challenges with respect to data readiness, timing of data collection, and consistency with other databases with respect to definitions.

Approach

Given the issues inherent in the available data (described above), we attacked the estimation problem via stratification—in essence, subdividing the big problem of generating statewide estimates of stocks and flux into several subproblems, each addressing one or more of the following eight forest strata: NFS timberland, NFS other forest, NFS reserved, other public timberland, other public other forest, other public reserved, private timberland, and private other forest, or aggregations thereof. Note that in the lexicon of FIA, ONF includes both other public and private (which in turn includes both industry and other private). Note also that this use of the term "forest strata" (above) has nothing to do with the strata-based inventory described in the "Data Sources" section. We are still relying on systematic, grid-based inventories, but are analyzing owner/productivity/reserve-class-based strata within those systematic inventories separately.

Although it is not strictly necessary to analyze each stratum separately, doing so allows for more critical analysis, review, and reasonableness checking. It cannot be overemphasized that, although our analysis generates estimates for these strata, in many cases, the standard errors are quite large (particularly for the relatively small and heterogeneous strata, such as other public, and for nearly all of the calculated fluxes), and the single stratum estimates should not be relied upon. The objective of the analysis is statewide estimates, and it was our hope that these would be more robust than nearly any of the individual stratum estimates, except those for ONF timberland.

Biomass estimates were made for the five major forest carbon pools: live above-ground, live belowground, standing and down dead wood, litter, and soil organic carbon.

Methods

Biomass estimates were made for the five major forest carbon pools: live above-ground, live belowground, standing and down dead wood, litter, and soil organic carbon. Where equations yielded biomass, estimates were converted to estimates of the associated carbon pool via application of the conversion factor 0.5 (U.S. Environmental Protection Agency 2007).

Calculation of Live Tree Aboveground Carbon

We subdivided the live aboveground pool into live tree and understory vegetation because the live tree pool is amenable to direct and comparatively precise estimation based on detailed inventory measurements, as compared to the understory component, which is derived from coarse models. For live-tree aboveground biomass, we used both local volume equations used by PNW-FIA coupled with species-specific parameters for specific gravity and the national-level equation system developed by Jenkins and others (2003, 2004) to highlight the effect of model selection on estimates of stocks and fluxes. Although we believe the PNW volume equations to biomass calculation to carbon pathway better reflects true carbon stocks and fluxes for California, others are routinely using the Jenkins equations for state-level analysis, in part because they are embedded in analyst-friendly accounting systems such as the Carbon Calculation Tool (Smith et al. 2007). The major difference between these two calculation pathways is that the local or regional equations are tree species-specific, whereas the national model is very general and groups about 400 tree species nationwide into 4 hardwood species groups, 5 softwood species groups, and 1 woodland species group. In essence, under the Jenkins approach, a single live-tree aboveground biomass equation will be applied to several tree species classified in the same species group for the national model. Another difference is that the PNW equations are functions of both diameter and tree height, whereas the Jenkins equations depend only on tree diameter. Biomass in both cases was converted to carbon via the factor 0.5.

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Calculation of Other Carbon Pools

All other carbon pools were calculated using methods developed by the USDA Forest Service (U.S. Environmental Protection Agency 2007, Smith and Heath 2002, Smith et al. 2007). The equations are developed by broad forest type groups. Understory vegetation carbon and down dead wood carbon are estimated as a proportion of live tree carbon (including above and belowground), standing dead wood carbon as a function of growing-stock volume, and forest floor (litter) carbon as a function of stand age.

Estimation of Carbon Stocks and Fluxes by Stratum

Outside of national forest timberland—

The ONF timberland (forest land owned privately or by government agencies other than the Forest Service, capable of producing at least 20 $ft^3 \cdot ac^{-1} \cdot yr^{-1}$, and not within areas formally withdrawn [reserved] from timber management as would be the case for parks and wilderness) has been regularly assessed by PNW-FIA for decades. The assessments pertinent to the calculation of 1990 carbon are the 1984 and 1994 California periodic inventories conducted by the PNW-FIA Program. We relied on the 94_CA_Change database, derived from these inventories, which contains measurements of trees inventoried in both the 1984 and 1994 inventories on ONF timberland, including, for example, diameters and heights, which can be used with species-specific volume equations to estimate total stem volume and somewhat less species-specific (i.e., where equations were lacking, an equation from a similar or related species was used) equations to estimate branch and bark biomass. For each tree, stem biomass was calculated from stem volume and the specific gravity of the wood of that species. Live-tree biomass was expanded to a per-acre basis using tree size-appropriate expansion factors (trees had been selected for measurement via variable-radius sampling so tree expansion factors differed), and then expanded again with plot expansion factors and condition proportions to account for the sampled trees' biomass representation in the larger landscape. There are a total of 4,824 plots in the 1994 change database; 1,444 of these plots contain tree-level information, and 963 plots are classified as ONF timberland representing 7.97 million acres—7.54 million acres of private timberland and 0.43 million acres owned by other public entities (e.g., state agencies and federal agencies other than the national forests).

Survey dates (decimal years) for 1984 and 1994 on ONF timberland are shown in the following tabulation.

Survey84	**Survey94**	**Number of plots**	**Average survey84**	**Average survey94**
81	91	70	81.53	91.80
81	92	215	81.67	92.60
81	93	103	81.67	93.52
81	94	2	81.67	94.50
82	91	200	82.45	91.67
82	92	147	82.55	92.58
82	93	185	82.67	93.66
82	94	4	82.46	94.46
83	91	3	83.75	91.53
83	92	3	83.69	92.69
83	93	23	83.58	93.54
84	91	2	84.50	91.63
84	92	3	84.53	92.61
84	93	1	84.50	93.67
84	94	2	84.71	94.75

Plot-level, live-tree biomass (stem + bark + branches) and biomass of other pools were calculated for each inventory date, and annual rates of biomass change calculated as the biomass difference divided by the plot-specific remeasurement interval (generally 10 years, ± 1 year). These were then converted to carbon stocks as survey1984 and survey1994 and annual carbon flux over this period for each plot. Plot-level annual flux was used to interpolate to arrive at an estimate of 1990 carbon stocks on ONF timberlands using the plot-specific information on interval length between survey date in the (nominal) 1994 inventory and year 1990. Total 1990 carbon stocks on ONF timberland was then summarized by summing representationally weighted 1990 carbon stocks for all plots.

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Live-Tree, Aboveground Carbon on All Other Strata

Carbon stocks on all other strata had to be estimated from post-1990 inventory data. Extensive and laborious attempts were made to estimate carbon flux for these other strata, but none were fully successful.

For reasons discussed above, direct comparison between population and subpopulation total estimates from the IDB and NIMS is not feasible (differences are more an artifact of the accounting strategies attempted than genuine signal). To work around some of these issues for this analysis, a "paired plot" database was developed that includes only periodic plots that were visited again during the annual inventory; however, the sample design was different between these inventories (i.e., the plot footprint) so few of the same trees are remeasured, and such remeasurement was not accounted for in this analysis. Because the plot footprints do overlap partially, the covariance in equation 1 is not zero, but also not readily determinable. For this analysis, we make the conservative assumption that there is no footprint overlap or linkage between plots from inventories taken at different times, so assign the covariance term as zero (thus likely overstating the sampling error). Because of differences in area estimates among inventories, we calculated biomass or carbon density (i.e., biomass or carbon per acre) and, except for ONF timberland (analysis of which was done entirely with the 1994) change database described earlier, relied on the area estimates from NIMS for each stratum to expand these densities into carbon quantities.

Given that (1) between the periodic and annual inventory, only six plots converted out of forest (four from oak woodland to urban, one from oak woodland to vineyard, and one from timberland to ski area); (2) these represent conversions of only about 20,000 acres per year out of 33 million forested acres; (3) most of these

Although we generated approximate annualized carbon flux statistics this way for all NFS forest combined (timberland, other forest, and reserved) and for the portions of unreserved other forest that were represented by data in the IDB, the approximated sampling error of these fluxes was large and always greater than annual flux (such that even a 66 percent confidence interval would include zero flux).

conversions are from relatively low carbon systems (oak woodland); and (4) in most of these cases, there is a strong possibility that some vegetation is retained, it seems reasonable to assume that conversion of forest land to date has had a negligible impact on carbon stocks and flux in California, which supports the use of NIMS area estimates (Bechtold and Patterson 2005) in all analyses.

Although we generated approximate annualized carbon flux statistics this way for all NFS forest combined (timberland, other forest, and reserved) and for the portions of unreserved other forest that were represented by data in the IDB, the approximated sampling error of these fluxes was large and always greater than annual flux (such that even a 66 percent confidence interval would include zero flux). Moreover, because the IDB contains no tree data for reserved lands outside of national forests, this analysis could not estimate fluxes for that stratum.

We also calculated flux from the annual inventory data by splitting that data set into two, 3-year periods (a 2001–2003 block and a 2004–2006 block), referenced hereafter as a NIMS 2-block analysis. By calculating the carbon totals for each period, by stratum, and dividing the carbon stock difference between these two periods by 3 years, we obtained estimates of annual flux.[4] Again, approximated sampling errors of the block carbon estimates were large, and those of the flux, even larger, and in every case, approximated sampling errors were larger than the annualized flux. Sign and magnitude of the fluxes were consistent for private and other public other forest between this analysis and the IDB paired plot estimation, but signs were reversed on NFS flux (this analysis showed net sequestration, whereas the paired plot analysis showed net emissions). However, in no case could flux be established as significantly ($\alpha = 0.05$) different from zero.

We believe that the best, most complete and most reliable estimate of post-1990 carbon stocks can be found in the 6 years of annual inventory data for California in NIMS (analyzed as a complete inventory, not divided into blocks). Accordingly, we estimated stocks for every carbon pool type for every stratum. Against our better judgment, we also attempted to “move” the NIMS carbon estimates backward in time to 1990 by applying the fluxes calculated in the NIMS 2-block analysis. This sometimes produced absurdly low values of carbon, and for

[4] Note that this approach is mathematically equivalent (assuming the panels contain the same number of plots) as (1) computing differences between panels 2001 and 2004, panels 2002 and 2005, and panels 2003 and 2006; (2) averaging these three 3-year differences; and (3) dividing by 3 to get an annualized estimate. This approach uses all the data once and estimates change over the maximum period permissible. It also compares two clearly independent data sets, so the covariance term in equation (1) can be disregarded.

one land type (other public reserved), negative carbon stocks as of 1990. Partly because of such outcomes, we deemed this line of attack unsuccessful. It is likely that the circa 2003 estimate represented by the annual inventory is a better representation of carbon stocks circa 1990 than any plausibly defensible manipulation would achieve.

Results

Outside of National Forest Stock and Flux

The results in which we have the greatest confidence are the live tree, aboveground carbon stocks (296 Tg carbon) and flux (2.9 Tg carbon/year) on ONF (i.e., private and other public), unreserved timberland, shown in table 2. These results are the only ones derived from consistent remeasurement of the same plots and trees. Interestingly, the Jenkins equations (which are comparatively coarse in that they are not species specific, and rely on diameter as the only tree size metric) not only produce higher estimates of carbon (at both inventory occasions) relative to the volume to biomass calculation pathway used at PNW, they also produce estimates of live tree aboveground carbon flux that are 16 percent lower. This is a timely reminder of the tremendous influence that model selection has in calculation of

Table 2—Forest carbon (C) stocks and flux on ONF (outside national forest) timberland in 1990 in California using PNW 1994 change database (total 7.97 million acres of non-NFS timberland)

Year	Aboveground live tree (PNW)[a]	Aboveground live tree (Jenkins)[b]	Below-ground biomass	Under-story vegetation	Dead wood	Soil organic	Litter	Total[c]
Survey 1984								
(TgC)	274.48	288.74	59.45	10.08	59.72	134.43	94.10	632.26
1990 Estimates								
(TgC)	296.47	307.20	63.18	10.76	61.86	133.72	93.00	658.00
Survey 1994								
(TgC)	303.95	313.38	64.43	11.09	62.79	134.00	93.24	669.50
Flux (TgC/yr)	2.879	2.432	0.492	0.086	0.287	-0.094	-0.136	3.514

[a] The live tree aboveground biomass is calculated based on the equations developed by Pacific Northwest Research Station, Forest Inventory and Analysis Program.

[b] The live tree aboveground biomass is calculated based on the Jenkins equations.

[c] The total carbon density or density change does not include the column using Jenkins equations (aboveground live tree [Jenkins]).

carbon budgets; for more on this topic, see Melson (2004). Also of note is that, although there are other carbon pools that in combination rival live-tree above-ground in size (e.g., dead wood, soil organic, and litter), the flux contributed by these other pools (as modeled) is comparatively slight.

Carbon Densities and Stocks by Stratum and Carbon Pool

Tables 3 and 4 report carbon density and stocks data for all forest lands in California. All columns for private and other public timberland are carried forward from the analysis completed for table 2 (described above) and are assessments

Table 3—Average carbon density by ownership and carbon pool in California

Ownership	Forest area	Aboveground live tree biomass[a]	Below-ground biomass	Under-story vegetation	Dead wood	Soil organic	Litter	Total
	Million acres	– – – – – – – – – – *Metric tons of carbon per acre* – – – – – – – – – –						
National forest:								
Timberland	9.275	38.247	9.595	1.499	9.652	16.799	10.414	86.207
Other unreserved	2.265	9.100	2.417	13.546	1.402	7.481	5.464	39.410
Other reserved	3.366	34.248	8.877	3.284	9.049	15.748	10.796	82.003
Other public:								
Timberland[b]	0.428	37.198	7.927	1.350	7.762	16.778	11.669	82.684
Other unreserved	1.795	6.952	1.523	5.668	0.880	7.252	4.761	27.035
Other reserved	2.485	45.549	9.809	10.237	8.957	15.266	11.501	101.319
Private:								
Timberland[b]	7.542	37.198	7.927	1.350	7.762	16.778	11.669	82.684
Other unreserved	5.660	12.107	3.010	2.040	1.823	10.124	7.064	36.169
Subtotals								
Timberland	17.245	36.099	8.532	1.506	7.895	16.341	10.703	81.076
Other unreserved	9.720	10.379	2.591	5.975	1.545	8.881	6.218	35.589
Other reserved	5.851	39.047	9.273	6.237	9.010	15.544	11.096	90.206
Total	32.816	30.494	7.248	3.415	6.580	14.420	9.704	71.861

[a] The live tree aboveground biomass is calculated based on the equations developed by Pacific Northwest Research Station Forest Inventory and Analysis Program (PNW-FIA).

[b] Timberland area and carbon density for other public and private (outside national forest) use 1994 change database data from PNW-FIA.

Table 4—Estimated total carbon on forest land by ownership and carbon pool in California

Ownership	Forest area	Aboveground live tree biomass[a]	Below-ground biomass	Under-story vegetation	Dead wood	Soil organic	Litter	Total
	Million acres	– – – – – – – – – – – – – *Teragrams carbon* – – – – – – – – – – – – –						
National forest:								
Timberland	9.275	354.73	88.99	13.91	89.52	155.81	96.59	799.55
Other unreserved	2.265	20.61	5.48	30.69	3.18	16.95	12.38	89.28
Other reserved	3.366	115.29	29.88	11.06	30.46	53.01	36.34	276.04
Other public:								
Timberland[b]	0.428	15.92	3.39	0.58	3.32	7.18	4.99	35.39
Other unreserved	1.795	12.48	2.73	10.17	1.58	13.02	8.55	48.53
Other reserved	2.485	113.17	24.37	25.43	22.25	37.93	28.58	251.73
Private:								
Timberland[b]	7.542	280.55	59.79	10.18	58.54	126.54	88.01	623.60
Other unreserved	5.660	68.53	17.04	11.55	10.32	57.30	39.98	204.72
Subtotals								
Timberland	17.245	651.20	152.17	24.67	151.39	289.53	189.59	1,458.54
Other unreserved	9.720	101.62	25.25	52.41	15.07	87.27	60.91	342.52
Other reserved	5.851	228.45	54.25	36.49	52.72	90.94	64.92	527.77
Total	32.816	981.28	231.66	113.56	219.17	467.74	315.42	2,328.83
Total CO_2 equivalent[c]		3,601.28	850.21	416.78	804.37	1,716.59	1,157.58	8,546.82

[a] The live tree aboveground biomass is calculated based on the equations developed by Pacific Northwest Research Station Forest Inventory and Analysis Program (PNW-FIA).

[b] Timberland area and carbon density for other public and private (outside national forest) use 1994 change database data from PNW-FIA.

[c] Total carbon dioxide (CO_2) equivalent is calculated, in terragrams, as 3.67 times Tg carbon.

(based on plot-by-plot interpolations between the 1980s and 1990s field visit dates) for the year 1990. All other strata are derived from the annual inventory (NIMS) for 2001–2006, a comprehensive inventory that samples all forested land in California at the same intensity, including (for the first time) parks and other reserved areas. The average inventory year for the NIMS data is 2004. With 60 percent of the annual inventory plots in California already collected, we are likely at a point where stratum totals for the larger strata will not vary so much from year to year. These are the first inventory results in California to characterize carbon stocks on all forested land (forested by FIA definition, that is). As annual inventory rolls forward and we remeasure these plots, we will be well-positioned to track carbon flux—probably as a rolling 5-year average (i.e., using five panels, or 50 percent of the plots), beginning in 2016.

Carbon density on timberlands in ONF unreserved timberland in private and other public is about 10 percent less in the NIMS data than in the 94 change table estimate (carbon density estimates derived from the 94 change table replaces the NIMS values in tables 3 and 4 for these strata). This is likely due to the additional 1.6 million acres of timberland as defined in NIMS, most of which was categorized as oak woodland in the periodic inventory (and in the IDB database). That forest type generally has a lower carbon density, so adding acres of it would tend to reduce average carbon density on timberland somewhat. Because the estimates in the 94 change tables relate only to the area classified as timberland in the periodic inventory, the periodic timberland area is used in lieu of the NIMS timberland area in these tables, and the excess timberland acres are recategorized to other forest. A remarkable 23 percent of the state's live-tree carbon is estimated to occur on reserved lands (which are 18 percent of the state's forest area), about half of this in NFS wilderness and the other half in state and national parks. And carbon stocks on all NFS strata combined represent more than half the statewide total.

A remarkable 23 percent of the state's live-tree carbon is estimated to occur on reserved lands (which are 18 percent of the state's forest area), about half of this in NFS wilderness and the other half in state and national parks. And carbon stocks on all NFS strata combined represent more than half the statewide total.

Carbon Fluxes Calculated From Annual Inventory Data

Comparing the PNW and Jenkins live-tree aboveground carbon densities in table 5a, we see that the Jenkins estimates are generally (though not always) higher, sometimes substantially. Although the discrepancy between the PNW-derived and Jenkins estimates on timberland are relatively low (about 10 percent, comparable with the discrepancies observed for the 1994 change tables), the discrepancies are much greater for some of the strata, such as NFS reserved. If the literature equations on which the Jenkins equations are based were derived primarily for trees on timberland, this could explain the higher estimates in reserved areas, where in general, site quality is lower, so trees of a given diameter are likely to be shorter. Because the PNW calculation methods account for height and the Jenkins equations do not, use of Jenkin's equations outside of timberland may be problematic in terms of upward bias, not just in California but wherever large areas of lower site class forest land exist.

Table 5a—Carbon density by ownership and carbon pool in California from NIMS database 2001–2003 and 2004–2006

Ownership	Forest land	Aboveground live tree (PNW)[a]	Aboveground live tree (Jenkins)[b]	Below-ground biomass	Under-story vegetation	Dead wood	Soil organic	Litter	Total[c]
		Megagrams (metric tons) of carbon per acre							
				Block 2001–2003					
National forest	Timberland	38.15	45.65	9.57	1.36	9.85	16.95	10.58	86.46
	Other unreserved	8.94	11.84	2.41	15.88	1.39	7.19	5.60	41.40
	Other reserved	33.70	41.78	8.76	3.49	9.14	16.12	11.06	82.27
Other public	Timberland	36.33	39.21	7.95	3.52	5.71	13.72	10.41	77.64
	Other unreserved	7.29	8.60	1.68	5.78	0.90	7.24	6.02	28.92
	Other reserved	39.52	43.46	9.01	10.18	8.66	15.85	12.32	95.54
Private	Timberland	34.38	37.23	7.64	1.25	6.72	16.95	11.71	78.64
	Other unreserved	11.69	15.41	2.95	1.80	1.78	9.88	8.87	36.97
All owners	Timberland	36.34	41.54	8.62	1.39	8.25	16.83	11.10	82.53
	Other unreserved	10.23	13.34	2.60	6.40	1.53	8.71	7.50	36.97
	Other reserved	35.96	42.43	8.86	6.09	8.95	16.01	11.55	87.43
All forest		29.76	34.66	7.16	3.46	6.70	14.66	10.28	72.02
				Block 2004–2006					
National forest	Timberland	38.26	46.02	9.61	1.74	9.31	16.58	10.13	85.63
	Other unreserved	10.19	13.29	2.69	11.43	1.51	8.30	5.49	39.61
	Other reserved	35.54	43.86	9.19	3.40	9.05	15.38	10.46	83.01
Other public	Timberland	32.02	34.91	7.15	3.33	4.63	12.29	8.94	68.37
	Other unreserved	6.36	6.29	1.24	4.91	0.77	6.66	3.16	23.10
	Other reserved	49.30	49.54	10.31	10.18	9.07	14.68	10.59	104.12
Private	Timberland	32.42	35.08	7.18	1.38	6.00	15.77	10.37	73.13
	Other unreserved	12.30	15.64	2.99	2.34	1.85	10.33	4.49	34.31
All owners	Timberland	35.13	40.18	8.31	1.66	7.47	15.96	10.18	78.71
	Other unreserved	10.54	13.15	2.57	5.49	1.54	9.03	4.53	33.70
	Other reserved	41.78	46.43	9.70	6.48	9.06	15.06	10.52	92.59
All forest		30.82	35.25	7.28	3.35	6.43	14.26	8.98	71.11

NIMS stands for National Information Management System.

[a] The live tree aboveground biomass is calculated based on the equations developed by Pacific Northwest Research Station, Forest Inventory and Analysis Program.

[b] The live tree aboveground biomass is calculated based on the Jenkins equations.

[c] The total carbon density or density change does not include the column using Jenkins equations (aboveground live tree).

Table 5b—Carbon density flux by stratum and carbon pool in California between 2001–2003 and 2004–2006

Ownership	Forest land	Aboveground live tree (PNW)[a]	Aboveground live tree (Jenkins)[b]	Below-ground biomass	Under-story vegetation	Dead wood	Soil organic	Litter	Total[c]
		Metric tons of carbon per acre per year							
National forest	Timberland	0.038	0.121	0.014	0.128	-0.178	-0.125	-0.150	-0.274
	Other unreserved	0.415	0.483	0.095	-1.483	0.038	0.372	-0.035	-0.599
	Other reserved	0.612	0.693	0.142	-0.030	-0.029	-0.247	-0.200	0.249
Other public	Timberland	-1.436	-1.432	-0.267	-0.062	-0.360	-0.475	-0.491	-3.090
	Other unreserved	-0.309	-0.769	-0.148	-0.289	-0.045	-0.195	-0.953	-1.938
	Other reserved	3.260	2.025	0.432	0.000	0.134	-0.389	-0.578	2.859
Private	Timberland	-0.651	-0.714	-0.152	0.045	-0.240	-0.391	-0.450	-1.838
	Other unreserved	0.204	0.076	0.013	0.180	0.022	0.150	-1.457	-0.887
All owners	Timberland	-0.406	-0.454	-0.102	0.089	-0.261	-0.289	-0.305	-1.275
	Other unreserved	0.103	-0.064	-0.011	-0.304	0.002	0.107	-0.990	-1.093
	Other reserved	1.938	1.333	0.279	0.128	0.035	-0.317	-0.344	1.719
All forest		0.352	0.200	0.039	-0.038	-0.090	-0.132	-0.432	-0.301

[a] The live tree aboveground biomass is calculated based on the equations developed by Pacific Northwest Research Station Forest Inventory and Analysis Program.

[b] The live tree aboveground biomass is calculated based on the Jenkins equations.

[c] The total carbon density or density change do not include the column using Jenkins equations (aboveground live tree)

Note also how difficult it is to discern any meaningful pattern in how the estimates in the two blocks of annual panels vary; this can be attributed to the small sample size when only three panels are considered. Thus, the calculated fluxes also bounce around, in some cases almost certainly spuriously (e.g., on comparatively small strata such as other public other forest). Regrettably, reliable flux data are not yet available for ONF other forest and reserved lands or for any stratum within national forest, and the flux data that are available for ONF timberland cover **only** the 1980s to 1990s period (no current flux is available).

The carbon density fluxes in table 5b can be converted to carbon fluxes by multiplying by the corresponding areas for each stratum; however, because these fluxes are not significantly different from zero ($\alpha = 0.05$), the resulting estimates are not statistically defensible. Table 6 shows the annual density fluxes and their standard errors for live tree, aboveground carbon derived from the 2-block NIMS data set (2001–2003 vs. 2004–2006). For no stratum are these differences significantly different from zero at the 95 percent confidence level (2 standard errors). At the 66 percent confidence level (1 standard error), a few of the strata and their aggregates (other public reserved, reserved any owner, and ONF timberland) are significant, and all forest land comes close. This (66 percent) is a highly unusual significance level on which to base analysis (e.g., it means that in cases where there is truly no difference, one would expect that in one out of three tests, you would [erroneously] report differences as significant); however, Heath (2007b) reports that standards of evidence in national greenhouse gas (GHG) inventories are different from those used by the FIA Program, so this information may be of interest to some readers. Although the NIMS 2-block flux calculated for the strata covered by the 1994 change tables (ONF timberland) is much less than the 1990 value of 2.9 Tg/ac (in fact, it is negative), it is not significant at the 95 or even the 66 percent significance level. If one wanted to make interpretations based on the 66 percent significance level, it is striking that the all-forest-land flux (almost significant at the 66 percent level) appears to be much lower than the timberland flux in 1990, and is probably as high as it is only because of the apparently high flux on reserved lands. It is possible that when more data have been collected (e.g., such that the annual data can be split into two blocks of five panels) and the difference covers a longer period, sampling errors may be reduced to the point that confidence intervals will not include zero for at least some strata.

Table 6—Mean carbon density flux and sampling error[a] by stratum for the live tree, aboveground carbon pool in California between 2001–2003 and 2004–2006[b]

	Forest-land groups							
	All forest land		Timberland		Nonreserved, excl. timberland		Reserved	
Stratum	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	– – – – – – – – Megagrams (metric tons) of carbon per acre per year – – – – – – – –							
National forest	0.309	0.445	0.059	0.579	0.420	0.536	0.655	1.120
Other public and private								
Other public	1.488	1.751	-1.443	2.684	-0.305	0.459	3.274	3.088
Private	0.065	0.502	-0.656	0.658	0.203	0.387		
All other public and private	0.491	0.596	-0.719	0.644	-0.018	0.316	3.274	3.088
All forest land	0.369	0.384	-0.391	0.433	0.104	0.273	1.966	1.500

[a] Sampling error calculations were consistent with Bechtold and Patterson 2005.

[b] Carbon density estimates differ slightly from those in table 5b because the estimates in table 5b calculate density using the stratum area estimates from the full 2001–2006 NIMS database, whereas the differences in this table are calculated from densities based on the 2001–2003 and 2004–2006 2-block NIMS stratum area estimates.

Bottom Line

Table 7 shows estimates of stock change in live trees (aboveground part only) computed two different ways: via the NIMS 2-block approach and the IDB to NIMS paired plots approach. Estimated carbon stocks are also carried forward from table 4 to highlight how small the estimated changes are relative to stocks (on the order of 1 percent or less, and far less than the sampling error typical of forest volume, biomass, or carbon at the state scale). Except for the stock change on private and other public timberland shown in the NIMS 2-block table (these estimates are actually from the 1994 change database), none of the cells in these tables are particularly meaningful owing to lack of statistical significance. In the case of the IDB to NIMS analysis (1990s to early 2000s), the changes in inventory definitions made it impossible to report timberland and other forest separately, so it is not even possible to use the 1994 change table estimates for ONF timberland in that table. For that reason, we would place slightly greater confidence in the NIMS 2-block stock change table, bearing in mind that even for this table, most of the cells are not significantly different from zero. It must also be remembered that other than ONF timberland, the fluxes for NIMS 2-block are actually calculated for the early 2000s, and simply assigned as our best estimate of flux for 1990.

Table 7—Alternative calculations of annual change in carbon stocks in live trees (aboveground) in California and estimated stocks in live trees

Owner group	All forest land	Timberland[a]	Unreserved other forest	Unreserved subtotal	Reserved
		Teragrams of carbon per year			
Estimated annual carbon stock change (NIMS 2-block)					
National forest	3.352	0.352	0.940	1.292	2.060
Other public	7.701	0.155	-0.555	-0.400	8.101
Private	3.879	2.724	1.155	3.879	0
Total	14.933	3.231	1.540	4.771	10.161
Estimated annual carbon stock change (IDB to NIMS)					
National forest	-3.325	Not avail.	Not avail.	-0.631	-2.694
Other public	7.295	Not avail.	Not avail.	-0.806	8.101[b]
Private	-6.600	Not avail.	Not avail.	-6.600	0
Total	-2.630	Not avail.	Not avail.	-8.037	5.407
Stocks[c]					
		Teragrams of carbon			
National forest	490.630	354.730	20.610	375.340	115.290
Other public	141.570	15.920	12.480	28.400	113.170
Private	349.080	280.550	68.530	349.080	0
Total	981.280	651.200	101.620	752.820	228.460

Note: Estimates are for 1990, but contain a mix of data collected before and after 1990; fluxes on approximately 75 percent of the forested lands are derived from inventories post-1990. Estimates of stock change in these tables are, for the most part, not statistically significant ($\alpha = 0.5$).

[a] Other public and private derived from 1984–1994 change database.

[b] Other public reserved is from NIMS 2-block analysis because there are no data on this stratum from IDB.

[c] This table is derived entirely from the aboveground live tree biomass column in table 4.

The past 15 years have seen relative stability in the forces that could otherwise make carbon flux highly dynamic. For example, this period was not marked by a high incidence of large forest fires or widespread pest outbreaks, and NFS timber harvest declined rapidly through 1992 to a level much lower than in past decades. There were no large-scale changes in landowner class, or conversion to nonforest land uses. This is fortunate, because it supports the option of using more contemporary observations that are consistent and assigning them to 1990 as the best available estimate we can make today. There is no way to ensure that any manipulation of 2000s flux in forest carbon, undertaken to try to get a "1990 number," will not

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result in an estimate that is even less descriptive of 1990 emissions (e.g., adjusting carbon stocks on other public land backwards in time using the NIMS estimates for annual flux generates negative live tree carbon for one stratum). These tables are included in this report only because the request that motivated this analysis specifically mandated 1990 estimates of stock and flux. The sizable discrepancies between these tables (and between the NIMS and 1994 change database estimates for flux on ONF timberlands) should be ample evidence to discourage any temptation to rely on differencing inventories as a basis for estimating carbon flux. The state of the data is such that the best estimate of aboveground, live tree carbon flux at the statewide level is 2.879 Tg/yr on ONF timberland plus zero elsewhere, based on the fact that given the data in hand and the time available to analyze it, there is no significant difference for NFS and ONF other and reserved forest and the fact that alternative calculation pathways result in post-1990 fluxes of different signs (e.g., NIMS 2-block versus IDB to NIMS).

The principal difficulty with attempting to discern flux via stock change, when the estimates of stocks at two points in time are independent (or mostly independent, as in the case of IDB to NIMS), can be illustrated with a hypothetical example. Suppose the true stock at **both** time 1 and time 2 is 1,000 units of carbon (i.e., there is no real change over the interval), and the inventory at time 1 generates an estimate of 975 (with a sampling error of 5 percent), whereas the inventory at time 2 generates an estimate of 1,025 (again with a sampling error of 5 percent). In real inventories such as FIA, volume estimates rarely have a sampling error much less than 5 percent (and often it is larger). Were you to calculate flux as the difference between the estimated total stocks generated by these inventories, you would obtain 1,025 – 975 = 50 units or a slightly greater than 5 percent flux. However, the 66 percent confidence intervals around the inventory estimates are for 1: 926 to 1,024 and for 2: 974 to 1,076, so were you to conduct a sensitivity analysis even on these 66 percent confidence intervals, you would have to consider the possibility that flux could range between -50 (974 to 1,024) and +150 (1,076 to 926), or from -5 percent to +15 percent. Remember that in this example, the true flux is zero because the true stocks are identical at time 1 and time 2; even if it were nonzero but small, say 1 percent, the estimated flux would be in error by an enormous percentage over nearly all of this range. Were we to conduct sensitivity analyses using 95 percent confidence intervals, the range of possible values for flux would be even greater. So even though the individual inventory estimates are the best available information about stocks at the respective times (actually within 2.5 percent of the true value in our hypothetical example) and it may well be tempting to attempt to estimate change as the difference in estimates of stocks (as has been traditionally done for greenhouse gas inventories in the United States and elsewhere), unless change is very large, such estimates are as likely to be wildly incorrect as to be close to accurate. The lesson here is that although flux may be derived from stock change, it cannot be reliably derived from change in estimated stocks. The strength of the analysis for ONF timberlands is that as remeasures of tree attributes and accounting for mortality, removals, and ingrowth, it is an estimate of stock change, versus the analysis for the other strata, which are changes in estimated stocks.

In summary, this rapid response analysis has demonstrated that:

- Reliance on calculations of differences in estimated carbon stocks derived from national inventory data collected at different times is unlikely to produce meaningful results because:
  - Different inventory dates cover different forest strata (and only the most recent inventory covers all strata), protocols, and plot footprints, such that this approach subtracts "apples from oranges."
  - Some of the nationally published/posted data have been adjusted/calibrated to try to account for some of the discrepancies among dates, but such adjustments are incomplete and may introduce other, unintended consequences.
  - Carbon stock change appears to be such a small fraction of stocks that it is less than the sampling error of the total carbon estimates and thus statistically insignificant in most cases.
- Where plots and trees are completely remeasured such that samples at two points in time are not independent, the covariance term in the sampling error (equation 1) grows large, and the sampling error drops much lower than otherwise.
- As annual inventory progresses and plots are remeasured (with ingrowth, harvest, and mortality accounted for, and with direct measurement of dead wood), FIA is well-positioned to provide monitoring data on carbon flux into the future, as well as the basis for understanding the dynamics of interpool transfers (e.g., from live trees to wood products, bioenergy, or atmospheric emissions via fire).

Reliance on calculations of differences in estimated carbon stocks derived from national inventory data collected at different times is unlikely to produce meaningful results.

Next Steps

The results reported here for strata other than ONF timberland should be considered preliminary, with the possibility of improved estimates in the future contingent upon additional analysis that is beyond the scope of what could be accomplished within the time available for this analysis.

So what are the options for obtaining more reliable information on carbon flux (other than waiting for the annual inventory remeasurements to roll in)? One option is to assess flux on paired plots, looking only at the remeasured trees on the one subplot on which overlap was most complete. This approach was used in the growth, removals, and mortality analysis for the California 5-year report (Christensen et al 2008); however, in that case, it was restricted to conifers on timberland. Extending to other forest lands and considering hardwoods adds complications and would require additional modeling (as hardwoods are generally not bored for increment). There is a wealth of increment data that might be used in this analysis, but considerable analytic time would be required to model this successfully—most likely requiring several months of biometrician effort.

Another potentially productive avenue of inquiry would be to conduct analysis on the two panels of remeasured NFS annual plots that have been collected to date, and which will be loaded into NIMS in spring, 2008. Remeasurement analysis with NIMS data has not yet been attempted, so this would be new territory and unforeseen challenges could well arise. Because only two panels are available, sampling error will be very large, but at least the analysis would be based on remeasurements of all the trees on the plots (not just a subset as in the IDB to NIMS paired plots). Ultimately, if flux is to be determined by change in stocks, operationally on an ongoing basis, there may well be a need for many additional sample plots to reduce sampling error sufficiently for signal to be detectable over the short time horizons under which information is critically needed, for example, to monitor progress in achieving carbon sequestration.

Although tables 2 and 5b suggest that carbon flux in pools other than live trees is small, all of those data are generated by coarse-scale models, not measurements on FIA plots. Quite possibly, some of these fluxes are not small or will not be small in the future (e.g., in dead wood, if widespread fuel treatment occurs or if pest or disease outbreaks recruit large amounts of biomass into the dead wood pool). However, the time available to conduct this analysis and data readiness issues precluded using FIA field measurements of down wood and standing dead wood, for example, to estimate the dead wood pool. To have a system of accounting that is sensitive to such events argues for reliance on field-observed data rather than models for these pools. There is potential to generate accurate estimates of dead tree flux once annual inventory plots have been remeasured (an early opportunity to test this concept is presented by the remeasurements of annual inventory plots on NFS lands in the Pacific Southwest [Region 5]). Whether or not we are able to assess change in down wood will depend on whether we continue to measure that pool in the future, and by what protocol we measure it. At a statewide level, there is certainly good potential to generate estimates of down wood carbon stocks, and this information could be used to validate, check, and perhaps improve upon whatever are the currently "accepted" equations for this pool. With additional analytic support, it is not hard to envision a program of research that would use FIA understory vegetation data to validate or at least compare against the understory pool equations; this might be particularly important in the chaparral type, which can contain substantial amounts of woody biomass, but which releases surprisingly large amounts of carbon at relatively frequent intervals (via wildfires).

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Equivalents

When you know	Multiply by:	To get:
Acres	0.405	Hectares
Feet	.3048	Meters
Inches	2.54	Centimeter
Tons	.907	Metric tonnes
Megagrams	1,000,000	Terragrams

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