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Science & Policy Brief

Measuring Forest Carbon: Strengths and Weaknesses of Available Tools

Key Points

- Emerging policies to mitigate emissions of greenhouse gases, particularly carbon dioxide, together with widespread recognition of the important role of forests in the global carbon budget, have created a need to evaluate the carbon stored in forests and the changes in those stores over time.
- Tools available for estimating carbon stores in U.S. forests include four developed by the USDA Forest Service - General Technical Report NE-343 (GTR NE-343), the Carbon Calculation Tool (CCT), the Carbon On-Line Estimator (COLE), and the Forest Vegetation Simulator (FVS).
- These tools are appropriate for coarse-scale comparisons of forest carbon storage across large regions. For example, these tools reveal that public forestlands tend to store more carbon than private, and that forestland reserved from harvest tends to store more than non-reserved land.
- These tools use the best available information, provide ready public access, and several allow for frequent updates using the most recent surveys. However, users need to be aware of several important limitations that are not readily apparent in all four available tools:

1. These tools have been based largely on Forest Inventory and Analysis (FIA) data, which was initially developed to measure merchantable timber volumes and provides no direct measurements for many important forest carbon pools.
2. Available measures cannot reliably estimate year-by-year

PHOTO COURTESY DAVID DAIL

With increasing attention to climate change, there is growing recognition of the capacity of forests to store vast amounts of carbon, and a growing need to measure these stores accurately. Techniques range from site-specific data collection (as in this photo from Howland Research Forest in Maine), to broad regional and national carbon estimates.

additions to forest carbon stores, due to estimation errors and data gaps.
3. The tools provide estimates for the recent past, but cannot be used to assess the potential for increasing future carbon storage in U.S. forests.
4. Estimates may be too low for carbon stored in old-growth forests, which differ in several important respects from mature second-growth.
5. These tools lack adequate precision for documenting sequestration for forest carbon offset projects; field sampling is critical for such projects.

- New FIA survey methods will eventually provide data for some of the non-tree pools and ensure more consistent coverage nationwide. Unfortunately, at the current pace and given limited funding it will be many years before complete coverage is available for these new measures.
- Given incomplete information about forest carbon, climate change policies should focus primarily on direct emissions reductions. Rather than rely on uncertain carbon accounting to mitigate climate change, forest carbon should be protected as a natural asset along with the many other important services that healthy forests provide – from clean water to wildlife habitat.

To help users understand both the potential and the limitations of these tools, this report will explain four carbon measurement tools, illustrate their use through selected examples, and point out likely gaps or inaccuracies that may be remedied in the future by planned improvements in data collection and research.

Forest Carbon Accounting

Since the 1990's, when global climate change was increasingly accepted as a reality, policy-makers at every level - from states to international agreements - have recognized the importance of forests in the global carbon cycle. Whether the focus is on preventing deforestation in the tropics, or on forest restoration in the Mississippi Delta, there is a growing consensus that protecting forestland and enhancing its carbon stores will be an important component of any attempt to mitigate climate change.

The past fifteen years have seen a multitude of climate change activities that rely upon information about forest carbon budgets.

- The United States signed the United Nations Framework Convention on Climate Change in 1992. Although we never signed the follow-up Kyoto Protocol, we do comply with this convention by reporting greenhouse gas emissions through the Environmental Protection Agency's Inventory of U.S. Greenhouse Gas Emissions and Sinks. The USDA Forest Service provides forest carbon estimates (including carbon stored in wood products in use and in landfills) for the "Land Use, Land Use Change and Forestry" section of this annual report.
- The U.S. Department of Energy Registry for Voluntary Reporting of Greenhouse Gases (called 1605(b) for provisions in the Energy Policy Act of 1992 that established the program) provides a national-level mechanism for voluntary reporting of emissions and sequestration projects. Because forest carbon pools tend to change slowly, and because direct sampling is costly, DOE

allows registry entrants to use look-up tables or models to estimate carbon stocks. USDA Forest Service tools provide some of these tables and models as well.

- In the absence of national action, regions and states have proposed strategies to reduce emissions or increase sequestration (often including forest offsets). The Regional Greenhouse Gas Initiative (RGGI), a cap-and-trade emissions reduction system scheduled for implementation in the northeastern U.S. in 2009, requires field sampling every five years for forest offset projects. The RGGI model rule does not recommend specific models or look-up tables as tools to estimate carbon stocks between sampling dates, but it does refer to the DOE 1605(b) standards.
- The California Climate Action Registry Forest Project protocol allows use of models, both to establish baselines and to predict additional carbon stores resulting from an offset project. Recognizing that models are imperfect reflections of a particular forest's condition, however, the Protocol requires periodic sampling at least every 12 years to verify that model predictions are accurate.

These efforts and many others require accurate assessment of the magnitude of forest carbon stores and their response to management actions over time. Highly precise measurements would require cutting down trees, digging up roots, collecting rotten logs and understory vegetation, extracting carbon from soils, etc., so carbon accounting necessarily relies on estimates. Estimates based on field sampling would be the next best alternative, but at a national level direct sampling across all regions and forest types and management regimes would be a daunting task. Hence, researchers have fallen back on existing national timber inventories to approximate forest carbon pools. As the United States moves toward regulation of greenhouse gas emissions, and possibly trading of forest carbon credits as offsets to industrial and transport emissions, it is important for policy-makers to understand the appropriate uses and the limitations of current carbon accounting tools.

Carbon Measurement Tools

Working from data designed primarily to track timber supplies, Forest Service researchers have patched together the available information and have begun to provide carbon estimation tools to the general public via published reports and user-friendly web access.[1] These tools represent an important step toward a better understanding of forest carbon storage, and can be used to make broad comparisons across large regions. However, they lack the calibration and resolution required for purposes of registering or selling carbon credits.[2] These tools are also limited to estimating current conditions; they do not provide information about the maximum capacity of our forests to accumulate additional carbon given adequate protection and restoration.

To help users understand both the potential and the limitations of these tools, this report will explain four tools, developed by the USDA Forest Service,

These tools represent an important step toward a better understanding of forest carbon storage, and can be used to make broad comparisons across large regions. However, they lack the calibration and resolution required for purposes of registering or selling carbon credits.

1 These tools are described and made available on a USDA Forest Service Northern Research Station web page at http://nrs.fs.fed.us/carbon/tools/

2 A recently-released guide, GTR NRS-18 (Pearson et al, 2007) provides a detailed protocol for measuring carbon sequestration for individual projects submitted to a registry or offered for sale as offsets.

Forest Carbon Measurement Tools

General Technical Report NE-343
- Carbon per acre in forest pools by stand age and forest type for large regions
- Carbon in wood products

Carbon Calculation Tool
- Total carbon in forest pools for states and U.S. by year after 1990
- Hectares of forestland and timberland for states and U.S. by year after 1990
- Change in carbon stock by year

Carbon On-Line Estimator
- Carbon per hectare in forest pools by stand age and forest type for selected area

Forest Vegetation Simulator
- Carbon in forest pools based on field inventory for specific parcels
- Projected carbon stores based on predicted growth, mortality, harvest, and disturbances

illustrate their use through selected examples, and point out likely gaps or inaccuracies that may be remedied in the future by planned improvements in data collection and research.

General Technical Report NE-343

The report titled *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States* (Smith et al, 2006) provides a quick and inexpensive approach for estimating ***carbon stocks for selected carbon pools by stand age***.

- Data include carbon density estimates (tons per acre or hectare) by stand age for six forest carbon pools[3] (above- and below-ground tree carbon are combined).
- Separate tables provide values for common forest types in each region, and for stands established on previously forested land (reforestation) or stands planted on non-forested land (afforestation). This distinction allows users to better estimate existing levels of forest floor and soil carbon, which will be higher initially on previously forested land.
- Report tables predict growing stock volume per acre from forest growth models, and convert growing stock to live and standing dead tree biomass using generalized equations. Other carbon pools (down dead trees, understory, and forest floor) are based on general relationships to growing stock, live tree carbon density, or stand age, with some of these relationships developed from a selection of FIA data and others from surveys of studies in the literature. This group of relationships is often referred to as FORCARB2.
- Users select the table for the region and forest type of interest and calculate total forest carbon by multiplying the appropriate density factor(s) by the acreages in each stand age and forest type. Annual accumulations of carbon can be approximated by subtracting older stand ages from current stand ages and calculating average increase per year. Due to uncertainties associated with all estimated pools, the accuracy of the results cannot be readily determined.
- Stand age is poorly defined for uneven-aged stands in areas where stand replacing disturbances are rare, which limits the applicability of these tables and the COLE tables by stand age described below. Differences in down dead, forest floor, and soil carbon for

[3] Pools are portions of the carbon stock that are physically separate and that play distinct roles in the carbon cycle. Definitions of forest carbon pools are mostly consistent among the tools reviewed here, though some combine or omit pools.

reforested and afforested stands are based on general assumptions and little data.
- This report also provides estimates of carbon stored in wood products, and decomposition rates over time, based on harvest volumes. Wood products carbon storage is a complex and controversial topic beyond the scope of this paper.
- This tool should be used for individual properties only as a decision tool to determine very roughly how much carbon is present and how much might accumulate in the future. It can be applied across broader regions with a bit more confidence, since the full range of variation within large regions will be reflected in growth equations and the FIA samples on which predictions are based.

Carbon Calculation Tool (CCT)

This tool provides annual estimates of ***state to national carbon stocks and flux***[4] from 1990 through the present for seven major forest carbon pools (above and below ground tree carbon are estimated separately). It also provides acres of forestland and timberland, and volume of growing stock on timberland[5].

- CCT uses past and current Forest Inventory and Analysis (FIA) surveys for each state as raw data and automates the process of updating data files as new surveys are completed.
- It also uses allometric equations to estimate carbon content of individual trees measured on each FIA plot, applies a series of equations to estimate non-tree carbon pools based on estimated biomass on each FIA plot, and aggregates plot-level estimates to state level using plot expansion factors. CCT uses basic soil survey information to provide soil carbon estimates.
- It calculates a rough estimate of flux by assuming uniform average annual changes between known survey dates and applying those rates of change to earlier or later years.
- This tool may be useful for states or the nation to track forest carbon inventories at a broad landscape scale. It makes use of the newest available sampling data, though data for some plots will still be up to 10 years out-of-date.

Carbon On-Line Estimator (COLE)

This online tool provides ***forest carbon density estimates for areas as small as single counties*** within the continental Unites States for six carbon pools by stand age (similar to GTR NE-343 tables).

- Output tables present estimates by stand age for a selected region down to a single county, for all forests and for common forest types. It also provides mean values for the six carbon pools for each distinct forest type across the region, without separating into age classes.
- The user chooses filters from a set of FIA variables measured in all

JIM MCGRAW/TWS PHOTO ARCHIVE

Santa Fe National Forest.

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4 Stock is the total quantity of carbon stored at any one time. Flux is the change in the stock from one time period to the next (often a year).

5 Forestland includes all land at least 10% stocked with trees, or land formerly forested and not converted to other uses. Timberland is more narrowly defined as forestland that is not reserved from harvest activities and that is capable of growing at least 20 cubic feet per acre per year. Growing stock is trees at least 5 inches in diameter of commercially valuable species and form.

state surveys or that could be reconstructed from known variables (e.g. state/county, ownership; forest type; stand age; stand size; productivity class; reserved status, etc.).

- Estimates by age class are developed by fitting equations to the underlying data for the selected FIA plots. These data are themselves estimates based on limited field measurements. Individual tree biomass, for instance, is computed by FIA based on region-specific equations that convert diameter and height to biomass. Methods to calculate individual plot data for non-tree pools are similar to those used to create the GTR NE-343 tables and CCT estimates.
- Like the CCT tables, underlying data can be updated and new equations estimated as new FIA plots are entered into the on-line FIA database.
- COLE tables are used similarly to the GTR NE-343 tables, although COLE allows filtering by several additional variables beyond region and forest type. (For instance, a user could estimate total carbon stored on National Forests in a state, by multiplying acreages of that state's National Forests for each stand age or forest type by corresponding carbon densities.)
- This tool is still evolving. Theoretically, it can provide estimates that better fit the characteristics of individual forested properties. Since real forests seldom fit neat categories, the filtering is only as good as field staff classifications by forest type, stand age, etc. Filtering is also limited by the need for at least 20 plots to fit equations, and the assumed form of fitted equations produces some quirky results (see Methods and Limitations of Carbon Measurement Tools below).

Forest Vegetation Simulator (FVS)

Originally developed to estimate tree growth and yield, FVS is a complex model that can be optimized for site-specific conditions. It can produce ***stock and flux estimates at the stand level***.

- The tool combines the Forest Vegetation Simulator (FVS), a national growth model with regional variants, with some of the same methods as GTR NE-343, CCT and COLE to derive current and projected carbon storage estimates.
- FVS creates stand-level carbon stock estimates for eight pools: above- and below-ground live and dead tree biomass, down dead wood, forest floor litter, duff, and herbs and shrubs.
- The user must enter a few stand- and tree-specific data, then can choose to apply the default volume-based method or generalized biomass equations to estimate carbon pools, similar to those used in CCT and COLE. Users may enter additional site-specific data to improve estimates.
- This tool may be used to simulate changes in carbon stocks associated with prescribed fire or other management actions, to track the fate of carbon removed during harvest, and to assess how strategies to build carbon will affect other important forest conditions. See Methods and Limitations of Carbon Measurement Tools for caveats.
- It can be used to roughly estimate changes in carbon stocks or flux by calculating differences in stand carbon stocks between years.

Sample Tool Applications

COLE, CCT and GTR NE-343 are the tools most likely to be used by the public in assessing forest carbon stocks. Due to the coarse scale of the FIA data upon which they are built and the generalized equations which are used to estimate pools for which no data has been collected, these tools are best used for estimating regional (multi-county) or state level carbon stocks. Fluxes should be estimated only at time intervals which are appropriate to FIA sampling intervals.

The following examples illustrate how CCT and COLE can be used to make some general comparisons of carbon stores by state, by pool within the forest ecosystem, and by ownership. (Data for Alaska and Hawaii are so incomplete that even broad estimates are not yet available.)

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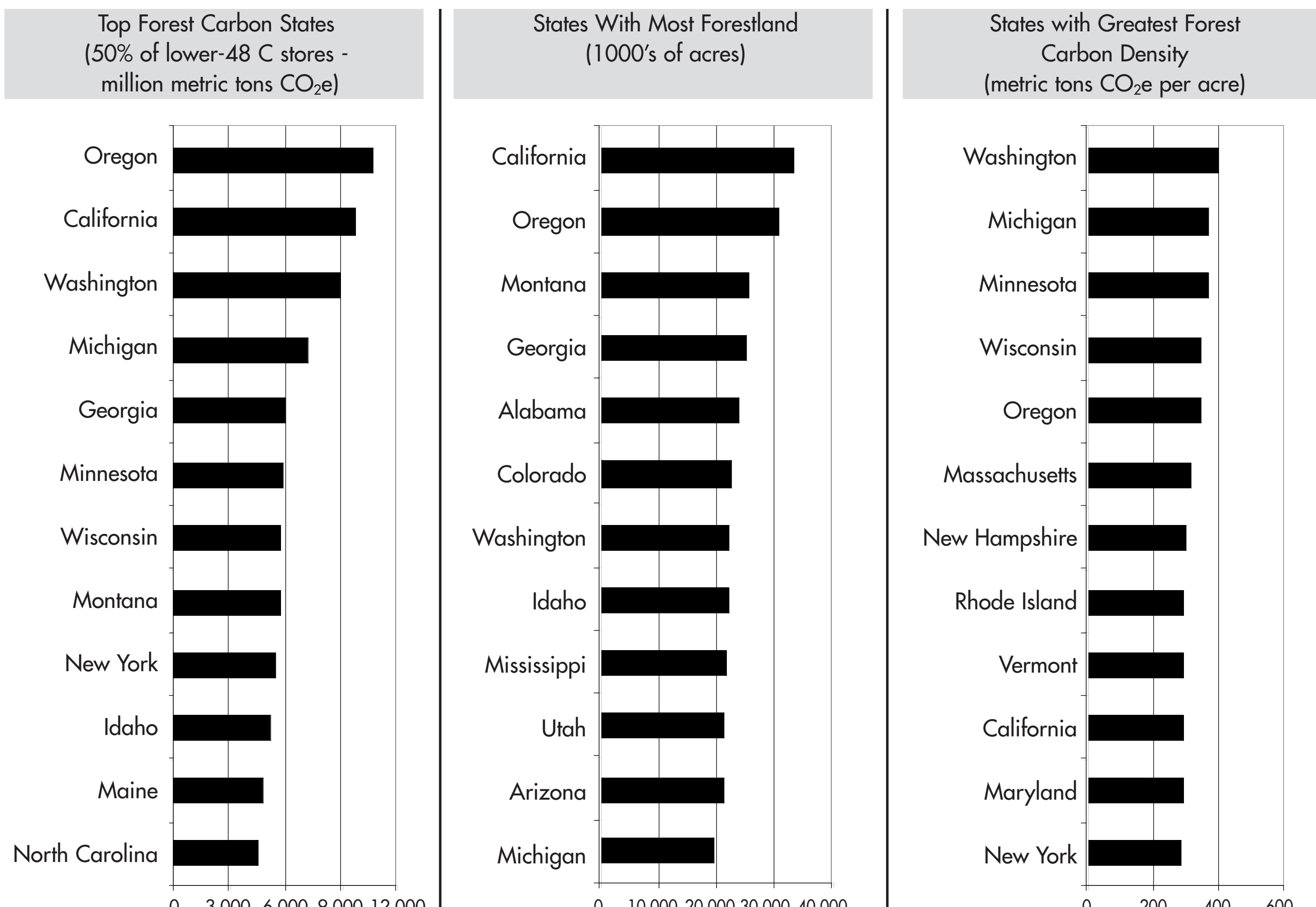
6 CO_2e stands for "carbon dioxide equivalent", a generally accepted measure for greenhouse gases. Multiplying the mass of carbon by 3.667 yields CO_2e.

FIGURE 1.

Total Forest Carbon, Forestland Acres, and Carbon Density by State in 2007



Source: Carbon Calculation Tool

State Level Carbon Accounting

U.S. forests store vast amounts of carbon, particularly in states with many forested acres and high levels of carbon per acre. Any national-scale effort to increase carbon sequestration in forests will likely focus on states with the most forestland and/or greatest potential carbon density (CO_2e6 storage per acre). Twelve states (left-hand chart in Figure 1) currently hold over 50% of the approximately 153 billion metric tons of CO_2e stored by forests in the contiguous United States. Some states are important because they have many forested acres (middle chart in Figure 1), while others (right-hand chart in Figure 1) have high forest carbon densities. It is not possible to assess the uncertainty of these estimates, and so the potential for large variation and error should be noted.

To put these numbers in perspective, the EPA estimated that total U.S. greenhouse gas emissions were 7,260 million metric tons CO_2e in 2005.

Regional Carbon by Pool

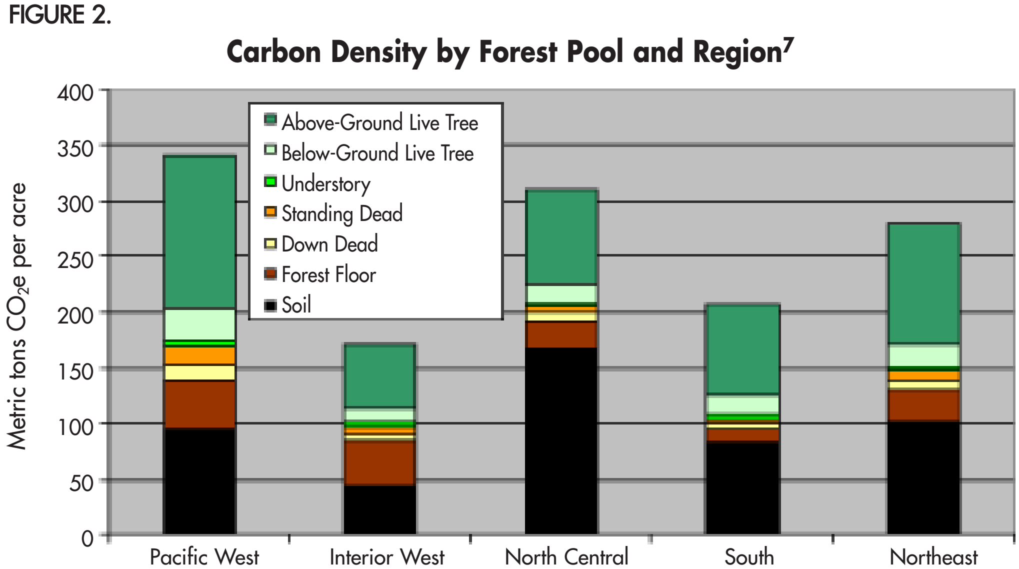
The distribution of carbon among forest pools varies widely across the landscape, but in general the amount of carbon stored above-ground in live trees – the pool we can measure with most confidence - is less than half the total. Landscape and climatic conditions affect the distribution of carbon among forest ecosystem pools (Figure 2). Wetter regions tend to fix carbon faster than drier ones, with a significant portion stored in live trees. Cooler regions - though they have a shorter growing season - also break carbon compounds down more slowly, allowing them to accumulate - particularly in soils, litter, and dead wood.

The Forest Service's nationwide FIA data provide a fairly good understanding of "growing stock" (volume of commercially valuable trees), which is closely correlated with above-ground live tree carbon. From this basic information, the other carbon pools – pools that together make up more than half of forest carbon stores - are estimated. Growth models predict the responses of live tree volume to management actions (though climate change could make their predictions less reliable). Very little is known about how other carbon pools respond to management.

Regional Carbon by Ownership

On average, public forestlands appear to hold more carbon per acre than private. Figure 3 indicates the density of carbon stores on public and private lands across five regions as defined in COLE. Note that densities are calculat-

FIGURE 2.

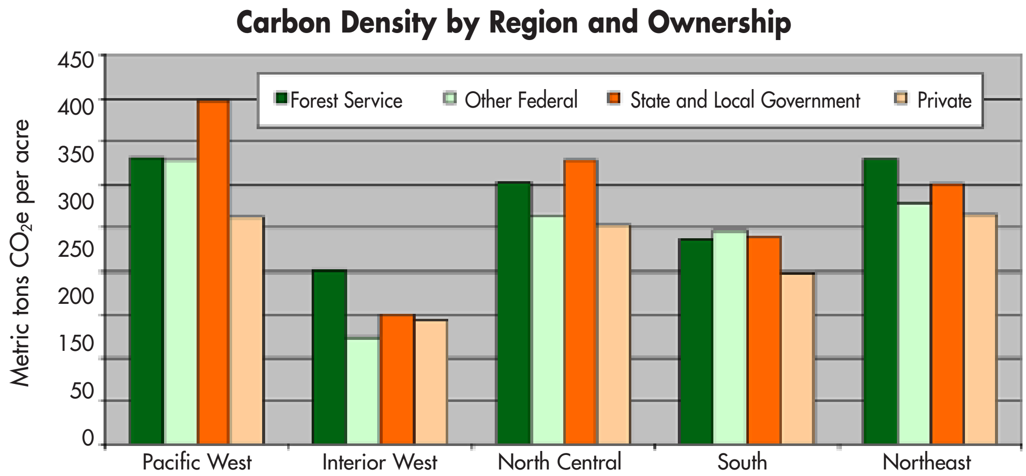


Source: Carbon Calculation Tool

[7] For consistency, this chart uses regions as defined in COLE. *Pacific West* includes CA, OR and WA. *Interior West* includes ID, MT, WY, NV, UT, CO, AZ and NM. *North Central* includes ND, SD, NE, KS, MN, IA, MO, WI, IL, MI, IN. *Southern* includes TX, OK, AR, LA, MS, AL, KY, TN, VA, NC, SC, GA, and FL. *Northeast* includes OH, WV, MD, DE, PA, NJ, NY, CT, RI, MA, VT, NH and ME.

ed across all acres classified as forestland; public lands in many states include some high-altitude or dry areas with low carbon stores.

FIGURE 3.

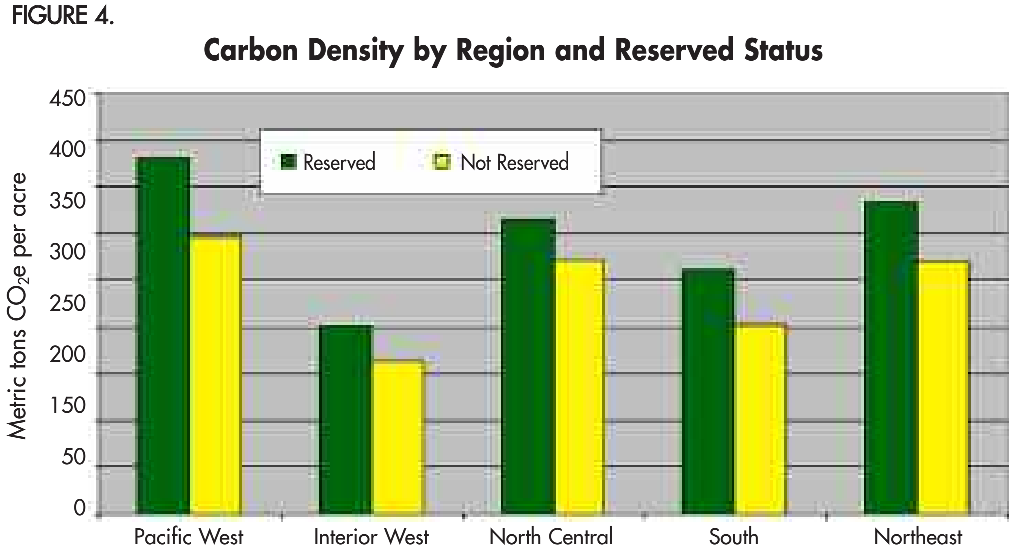


Source: Carbon On-Line Estimator

Regional Carbon by Reserve Status

Reserved forestlands typically hold more carbon per acre than non-reserved lands[8]. Figure 4 shows average carbon density by reserved status for five regions. Since many reserved areas are at high altitude or in dry or wet areas that are inherently low in biomass, this comparison does not fully capture the potential for reserved productive forestland to accumulate large stores of carbon. Where reserved forests support old growth, these figures likely underestimate carbon density (see Carbon Estimation Issues for Older Forests).

FIGURE 4.



Source: Carbon On-Line Estimator

Methods and Limitations of Carbon Measurement Tools

Direct measurement of forest carbon stocks would require cutting down trees, digging up roots, sifting soils for debris, oven-drying and weighing all material, etc. Since complete measurement is impossible, databases such as FIA collect easily-measured data such as tree diameter and height, then use equations to translate these parameters into approximate tree volume and other measures. Because they are readily available and cover forestlands nationwide, FIA surveys provide the basic raw data from which most national carbon estimates are derived. Each one-acre FIA sample plot represents about 6,000 forested acres, and over the past several decades resampling has occurred at 5-15 year intervals for most states. Future surveys will be done on an annual basis, which will improve flux estimates.

Some general limitations apply to all national estimates of forest carbon:

8 Reserved forestlands, as defined by FIA, are those where timber harvest is prohibited through statute or administrative designation. Examples include National Forest wilderness areas and National Parks and Monuments.

- ***The pools that store the most carbon are characterized with the least data.*** FIA surveys were originally designed to track commercial timber supplies, not carbon, so data on below-ground biomass, non-merchantable above-ground biomass, standing and down dead wood, forest floor, and soil carbon have not been consistently collected. Estimates for these pools use general relationships gleaned from various research studies across the country to predict carbon amounts from just a few direct measurements – species, diameter, and cull or dead status for trees, and region, forest type, and stand age for plots. Some forest types and carbon pools (generally the more valuable timber resources) have been intensively studied, while others of minor economic value are relatively little known.
- ***Model assumptions strongly influence estimates.*** Both COLE and the GTR NE-343 tables are based on even-age forests. The differences between reforestation (new forest established after the previous stand was removed by harvest or disturbance) and afforestation (new forest on previously cleared land) are based on very little real data. Clearcuts and stand-replacing natural disturbances have very different carbon implications, but both would be approximated by reforestation tables. These models are also not very helpful for estimating carbon stocks on uneven-age forests.
- ***The uncertainty of stock estimates is much larger than the estimated year-to-year change in stock.*** Annual removals of carbon dioxide from the atmosphere by U.S. forests are of great interest for their potential to offset current emissions from other sources. These flux estimates can be derived from changes in stocks over time. The uncertainty of stock estimates produced by the tools described here makes it impossible to predict the true magnitude of annual forest sequestration flux. According to CCT estimates, annual additions to forest carbon stores nationwide are less than 0.4% of total stores, while the uncertainty in estimating stores far exceeds 0.4%. Thus, these data cannot reliably determine the extent to which U.S. forests actually offset emissions.
- ***Time lags between FIA sampling also make it difficult to estimate carbon flux.*** Carbon stocks for years between periodic FIA inventory dates are interpolated assuming constant rates of change. This approach tends to produce flux estimates that are constant for several years, then make sudden jumps as new survey data become available. Recently instituted annualized surveys will improve this situation, but only a few selected plots are sampled each year, and because estimates roll together

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9 An example from the Department of Energy's 1605b registry illustrates why this is important. The registry employs a rating system to indicate the accuracy of sequestration estimates ("A" most accurate, "D" least) and a "B" rating is required to register reductions in GHG emissions. The COLE tool receives an "A" rating if "validated with data specific to the site conditions and management practices", or a "B" rating with no direct data collection (US DOE, 2007). The 1605b technical appendix for Forestry indicates that a "B" rating requires estimates within 20% of the true value with 95% confidence, a standard that COLE cannot meet.

several years of data they will always lag reality by several years.

- ***Inaccurate sequestration measures may lead to an underestimate of the nation's greenhouse gas footprint.*** Measurement errors matter when carbon flux is reported in voluntary registries, and even more so when offsets are marketed. Errors compounded from multiple steps and assumptions are extremely difficult to characterize. COLE tables by stand age, for instance, provide error estimates that indicate how well equations fit the input data. Remembering that the input data are themselves estimated from FIA plot or tree variables, and have their own estimation errors, the magnitude of the compounded errors is likely to be quite large but is entirely unattributed.[9]

Table 1 summarizes the methods and limitations specific to each tool and each carbon pool.

TABLE 1.

Estimation Methods and Limitations by Forest Carbon Pool

Forest Carbon Pool	Estimation Methods	Limitations
Above ground live tree	**GTR NE-343:** Growing stock from Aggregate Timberland Assessment Model (ATLAS) model, converted to carbon using stand-level biomass equations.	Data input are limited to FIA plots, which lack adequate numbers to develop precise estimates for less abundant forest types and conditions (e.g. old growth).
	CCT: Individual tree biomass estimated from FIA tree data using allometric equations, scaled up to plot (plot data used directly when tree data unavailable), expanded to state totals.	Allometric equations are scarce for large-diameter trees, particularly hardwoods. Biomass reductions for cull trees are also quite uncertain (Smith et al, 2003).
	COLE: Biomass from DRYBIOT field in FIA database (calculated from individual tree diameter and sometimes height), scaled up to plot. (Similar to CCT but allometric equations vary with FIA survey). Growth equation fitted to selected plots to produce values by stand age.	FVS and ATLAS models are by necessity based on historic forest growth over a relatively short time period. Future forest growth may change dramatically with climate. Species will probably differ in growth responses to CO_2 enrichment, changing competitive advantages and species mix. Pests, diseases, and extreme weather events have already increased the pace and severity of "natural" disturbance in many locations.
	FVS: Current inventory entered by user, future tree biomass predicted from regional growth/mortality equations and input management and disturbances.	
Below-ground live tree	**GTR NE-343:** Not estimated separately.	Measuring tree roots of various species and sizes is an expensive and difficult process, so few studies are available to develop accurate estimates.
	CCT: Allometric equations are applied to tree data when available, otherwise to plot values.	Definitions of root biomass vary among studies, thus data used to develop equations to predict belowground biomass may be based on a combination of coarse and fine roots at varying depths.
	COLE: Not estimated separately.	
	FVS: Determined from available allometric equations, then converted to proportion of aboveground biomass. Proportions modeled as functions of inverse diameter to reach asymptote for large trees.	

TABLE 1.

Estimation Methods and Limitations by Forest Carbon Pool

<table>
<tr><th>Forest Carbon Pool</th><th>Estimation Methods</th><th>Limitations</th></tr>
<tr><td>Understory</td><td>

GTR NE-343: Nonlinear equation related to live tree carbon density (by region and forest type). Maximum values set at about 2 to 5% of live tree carbon for low tree volumes, declining for higher tree volumes.

CCT: Similar to GTR NE-343

COLE: Same as above for individual plot values; equation fitted to selected plots to produce values by stand age.

FVS: COVER extension models canopy to predict understory growth conditions and estimate understory biomass. Equations based on limited forest types within 40 years of disturbance.

</td><td>

Understory measurements are only just beginning for FIA surveys, so few data are available to assess this pool.

Since the understory holds such a small percentage of total forest carbon, researchers conclude that intensive investigation would not be productive.

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<tr><td>Standing dead</td><td>

GTR NE-343: Equation related to live growing stock (by region and forest type), based on subset of FIA plots that measure standing dead trees.

CCT: Modified versions of GTR NE-343 equations (standing dead FIA data inconsistent).

COLE: Individual plot values from FIA database; growth equation fitted to selected plots to produce values by stand age.

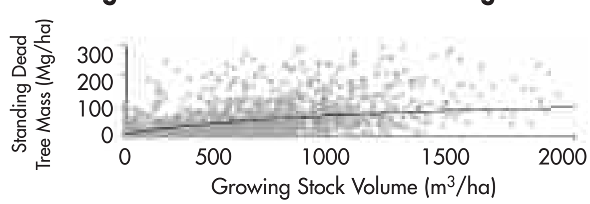
FVS: Growth models predict mortality that creates snags and falling or decaying of snags.

</td><td>

There is even greater variation in dead tree biomass and carbon density across sample plots than the variation for live trees (see Figure 5 below). With inadequate data to characterize dead trees in most past FIA surveys, the equations cannot accurately predict this pool from live tree biomass.

FIGURE 5.

Equations and Sample Points Relating Standing Dead Tree Biomass to Growing Stock



Estimated mass density of live and standing dead trees in PWW Douglas-fir forests on publicly owned land.

Source: Smith et al, 2003.

COLE currently uses standing dead tree measures directly from the FIA database, without correcting for missing or inconsistent data.

GTR NE-343 and COLE equations by stand age set this value to zero at a stand age of zero for both afforestation and reforestation tables. This assumption may be appropriate for an intensively manage forest, but would not be appropriate for stands regenerating after natural disturbances.

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TABLE 1.

Estimation Methods and Limitations by Forest Carbon Pool

Forest Carbon Pool	Estimation Methods	Limitations
Down dead	**GTR NE-343:** Ratios of down-dead to live-tree carbon density (by region and forest type). Reforestation tables adjust for a pulse of forest floor and down dead wood post-harvest. **CCT:** Similar to GTR NE-343. **COLE:** Same as above for individual plot values; equation fitted to selected plots to produce values by stand age, adjusted for reforestation tables to reflect higher levels after disturbance. **FVS:** Growth models predict mortality and subsequent toppling and decay.	Due to great variation in biomass and carbon density in down dead trees, this pool cannot be accurately characterized by generic equations. It has been measured only very sporadically by FIA surveys in particular states. Down dead wood varies considerably by forest stand, and is particularly prevalent in old growth forests which are represented by very few FIA plots. Reforestation assumptions do not reflect differences in harvest practice (e.g.whole-tree vs. cut-to-length), nor are they likely to describe natural disturbances.
Forest floor	**GTR NE-343:** Equations (by region and forest type) predict net accumulation by stand age up to a maximum. Decay of extra deposits after disturbance estimated separately for reforestation tables. **CCT:** Similar to GTR NE-343. **COLE:** Same as above for individual plot values; equation fitted to selected plots to produce values by stand age, adjusted for reforestation tables to reflect higher levels after disturbance. **FVS:** Equations estimate stocks, calibrated for most FVS variants; user can input values if known.	Existing studies of forest floor carbon were not systematic. Methods vary from study to study and some forest types may be under-represented. Maximum forest floor carbon levels for each forest type are set at the 95th percentile for all studies reporting on forests of at least "mature" age (15 to 60 years depending on region). If studies lack old growth representation, this value would understate the true maximum. Forest floor carbon after a clearcut is assumed to begin at "mature" forest levels. If deposits from logging residue or natural debris are higher than this level, carbon releases after disturbance may be higher than predicted.
Soil	**GTR NE-343:** Based on data from STATSGO, a national database of soil associations. Soil carbon is based proportionally on the soils present beneath each forest type. Data gaps are filled in with information from similar soils. Afforestation tables assume beginning value at 75% of mature forest value. **CCT:** Similar to GTR NE-343. **COLE:** Same as GTR NE-343 for individual plot values, equation fitted to selected plots to produce values by stand age for afforestation tables. **FVS:** Not estimated	STATSGO is a very coarse soils map. Mapping units combine many soil series that may have very different carbon densities. Variations in soil texture, mineralogy, moisture and temperature within a region can alter soil carbon content considerably. These variations are undetectable at the scale of the STATSGO database at present. This soil carbon measure also does not capture the variation associated with past land use history or current management, potentially underestimating the buildup of carbon stores on reforested farmlands. Research is underway to adjust soil carbon measures for past land use, and the new FIA design will collect information on soil carbon for selected plots.

Carbon Estimation Issues for Older Forests

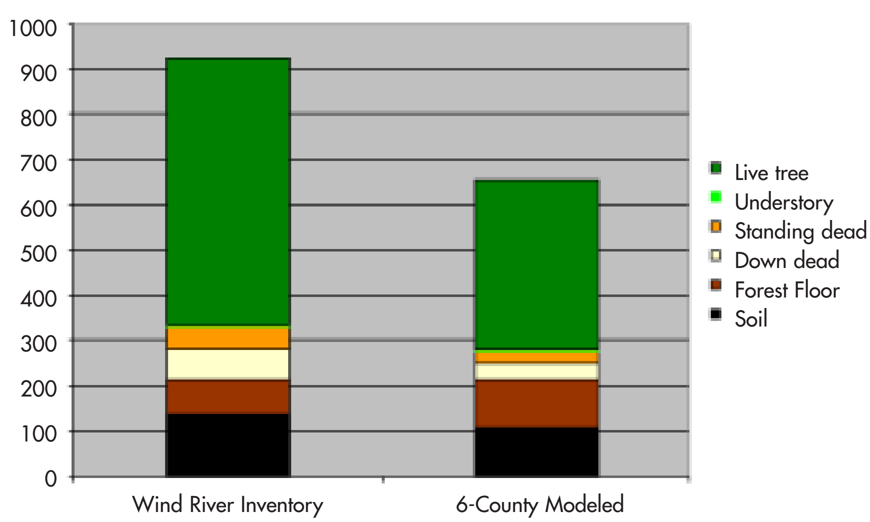
The measurement tools described above are based mostly on models of intensively managed forests and may well underestimate carbon stores on older or unmanaged forests. Figure 6 contrasts ground-based carbon measurements for the old-growth stand at Wind River on the Gifford Pinchot National Forest in southern Washington state with COLE estimates for the same forest type and geographic region. For this forest, the COLE estimate is 29% below estimates based on ground measurements.

There are several reasons why available tools may underestimate carbon stores on older forests.

- For very old trees, above-ground volume and carbon may not conform to standard dimensional equations. Allometric equations that predict tree biomass from diameter and species depend upon available research studies for particular species and tree diameters across the country. These equations underlie carbon estimates used by all four carbon measurement tools reviewed here.
- Earlier FIA surveys frequently undercounted reserved forestland where many older forests are found. Partly for this reason and partly due to the scarcity of reserves in many areas, COLE often has an inadequate number of plots to provide estimates for reserved status lands. GTR NE-343 tables end at stand ages of 90 to 125, depending on region and forest type. Likewise, the scarcity of old unmanaged stands means that FVS growth equations do not apply well to older stands, and may underestimate the life-spans of trees in such stands.
- Look-up tables from GTR NE-343, and the similar COLE equations by stand age for non-tree carbon pools, are based on models of forest growth on previously clearcut or nonforested land. Forests experiencing natural disturbance regimes do not fit either of these models well, particularly at very young and very old stand ages. For young stands, standing and down dead wood volumes will be much higher after fire, ice storm, or wind event than

FIGURE 6.

Site Sampling and Model Estimates for Wind River Old Growth Forest



Source: COLE and FORCARB2 equations [10]

[10] This chart uses COLE equations for live tree and standing dead tree carbon fitted to FIA plots in Douglas fir forest type in the smallest area surrounding Wind River that would provide a sufficient number of plots (Clark, Cowlitz, Klickitat, Lewis, Skamania, and Yakima counties). Since COLE does not provide equation coefficients for other carbon pools, understory, down dead, and forest floor estimates use standard region/forest type coefficients and FORCARB2 equations cited in U.S. EPA, 2007, Annex 3, Section 3.12 – Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands.)

after a clearcut harvest.

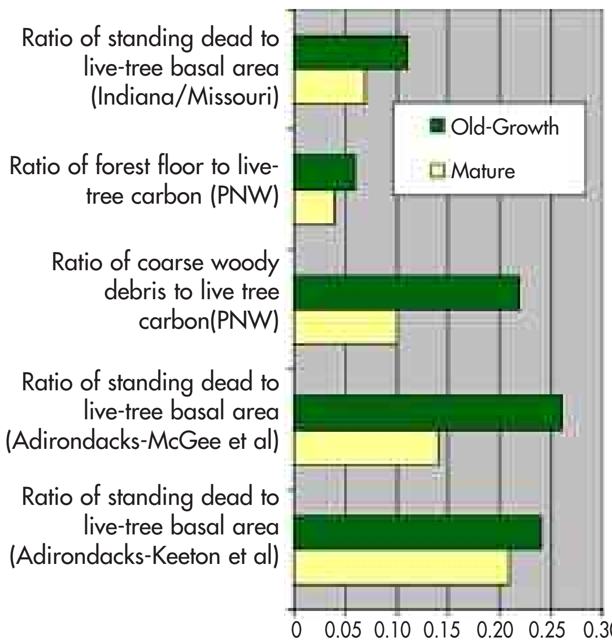
- In very old stands, standing and down dead trees may build well above levels typical of "mature" forests. Several studies have shown (Figure 7) that standing and down dead wood and forest floor carbon may build to much higher levels in old growth forests than in mature second-growth.
- When large dead logs eventually lose biomass through decay, much of the carbon will be captured in stable soil carbon pools that persist for hundreds to thousands of years. Yet standard soil measurements are unlikely to reflect high carbon storage in old growth soils. In fact, soil samples used for standard soil surveys tend to be taken in open fields when possible (for reasons of convenience and because of a focus on mapping agricultural soils) where soil carbon has been depleted by cultivation.

If inventory estimates fail to reflect actual carbon stocks, then flux derived from stock changes will not reflect the true potential for older forests to act as carbon sinks. Studies of the Wind River

FIGURE 7.

Comparisons of Mature to Old Growth Forests[11]

	Indiana/Missouri	
	Mature Second-Growth	Old Growth
Ratio of standing dead to live tree-basal area[12]	0.07	0.11
Down dead volume (m3/ha)	0.2 to 32	24 to 111
	Pacific Northwest	
	60-year old Forest	450-year old Forest
Ratio of forest floor to live-tree carbon	0.04	0.06
Ratio of coarse woody debris to live-tree carbon	0.02 to 0.10	0.22
	Adirondacks	
	Maturing	Old-Growth
Ratio of standing dead to live-tree basal area	0.14	0.26
Down dead volume (m3/ha)	61±16	139±22
Ratio of standing dead to live-tree basal area	0.21	0.24
Down dead volume (m3/ha)	86±34	164 ±40



[11] Indiana and Missouri study (Spetich, et al, 1999) compared standing and down dead wood on old-growth and mature (70 to 100 year) second-growth hardwood stands. Pacific Northwest study compared carbon stores in a 60-year-old Douglas-fir stand and a 450-year-old Douglas-fir/hemlock stand (Harmon, et al, 1990). Adirondacks study cited in first two rows (McGee, et al, 1999) compared old-growth to 90-100 year old even-aged second-growth northern hardwood stands. Adirondacks study cited in last two rows (Keeton et al, 2007) compared old growth stands with comparable second-growth stands (dominant canopy trees 80 to 150 years).

OREGON NATURAL RESOURCES CONCIL

Existing measurement tools are not well suited to measuring the vast stores of carbon in old growth forests.

old-growth forest indicate that it continues to sequester atmospheric carbon at 500 years stand age. Eddy-covariance studies that track carbon dioxide concentrations above the canopy indicate a carbon sink of 2.2 to 2.8 metric tons CO_2e per acre (Paw U et al, 2004), while stock change estimates indicate a smaller contribution of up to 0.3 metric tons CO_2e per acre (Harmon et al, 2004). Zhou and others (2006) found that soils in old-growth stands (over 400 years stand age) on a biosphere reserve in China continued to build carbon reserves during the period from 1979 to 2003. This active uptake of carbon runs counter to previous assumptions that old growth forests no longer actively sequester carbon.

Despite modest levels of current sequestration compared with younger stands, old growth forests may also be more resilient in the face of climate-related stresses that threaten the future of today's forest carbon sinks. Research suggests that old growth forests may be less susceptible to climatic fluctuations than young forests, including seasonal drought, allowing them to assimilate more carbon than younger stands (Anthoni et al. 2002).

Even if old growth forests fix carbon very slowly, conversion to younger managed forests results in a significant release of carbon to the atmosphere. Models indicate that it can take 100-200 years for regenerating forests to achieve the carbon storage of old-growth forests in the Pacific Northwest, even when storage in wood products from harvested timber is taken into account (Harmon et al. 1990; Law et al. 2001; Janisch & Harmon 2002).

Conclusion and Recommendations

The USDA Forest Service has provided timely information on a forest value that deserves wider public recognition and protection, and has developed tools that are accessible to a broad array of users. However, these tools come with significant limitations that must be understood by both policymakers and public. Accurate measurements of adequate precision are needed to set appropriate policies regarding forest carbon and greenhouse gas reduction. Overestimates of forest carbon sequestration, whether incorporated in a national greenhouse gas inventory or applied to registered or traded offsets, would undermine a necessary shift away from fossil fuels, and our forests would ultimately suffer from resulting climate-related stresses. Estimates that fail to fully capture the contributions of our oldest forests could encourage conversion to young plantations that ultimately fail to deliver the expected greenhouse gas reductions, while making the nation's forests less resilient to climate change.

As the United States moves rapidly toward a national cap-and-trade system, which will likely incorporate the trading of forest-based offsets, land management agencies and regulators must:

- Clearly explain the limitations of available tools and models that estimate forest carbon, especially for individual properties.
- Require rigorous field sampling to document increases in forest carbon stores claimed as offsets to regulated emissions sources.
- Accelerate the phase-in of the new national FIA survey design to improve information on standing dead, down dead, understory, forest floor, and soil carbon pools, and incorporate this new information in forest growth and carbon models.
- Support research that
  1. investigates the role of older forests in storing long-term carbon;
  2. assesses the potential to enhance forest carbon stores through reserves or active timber management; and
  3. evaluates strategies to help forest systems weather future climate stresses by harboring a diversity of species and creating stable microclimates.

Given incomplete information about forest carbon, climate change policies should focus primarily on direct emissions reductions. Rather than rely on uncertain carbon accounting to mitigate climate change, forest carbon should be protected as a natural asset along with the many other important services that healthy forests provide – from clean water to wildlife habitat. These values, including future forest sequestration, are threatened by coming climate changes, and their future depends upon effective policies that address the threat.

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