Investigation into Calculating Tree Biomass and Carbon in the FIADB Using a Biomass Expansion Factor Approach

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Abstract: *The official U.S. forest carbon inventories (U.S. EPA 2008) have relied on tree biomass estimates that utilize diameter based prediction equations from Jenkins and others (2003), coupled with U.S. Forest Service, Forest Inventory and Analysis (FIA) sample tree measurements and forest area estimates. However, these biomass prediction equations are not the equations used in the current public national FIA dataset (FIADB3), which utilizes regionally specific prediction equations, nor are they based on current FIA volume estimates. We describe and investigate an approach that is proposed for biomass estimates in the FIADB version 4 (FIADB4), due to be released in April, 2009, and that would produce national-level biomass and carbon estimates consistent with FIA volume estimates at the tree-level. The approach, called the component ratio method (CRM), is based on: 1) converting the sound volume of wood in the bole to biomass using a compiled set of wood specific gravities; 2) calculating the biomass of bark on the bole using a compiled set of percent bark and bark specific gravities; 3) calculating the biomass of tops and limbs as a proportion of the bole biomass based on component proportions from Jenkins and others (2003); 4) calculating the biomass of the stump based on equations in Raile (1982); and 5) summing the parts to obtain a total aboveground live biomass. Root biomass is also available as a proportion of the bole biomass based on component proportions from Jenkins and others (2003). The CRM approach is based on assumptions that the definition of bole in the volume prediction equations is equivalent to the bole in Jenkins and others (2003), and that the Jenkins and others (2003) component ratios accurately apply.*

We compare results between estimates calculated using equations in Jenkins and others (2003), current regional FIA equations, and this approach. The CRM approach is promising because the estimates are congruent with FIA volumes and compiled specific gravities. However, because FIA units currently use different volume equations the resulting estimates are not nationally consistent (that is, biomass of the same diameter and species tree will differ between regions). Because a number of volume equations are currently used by FIA, this approach can be complex for those wanting to take their own tree data and estimate biomass with FIA prediction equations especially when data cross regional boundaries. In the long-term, a planned and coordinated research study, as well as an accompanying operational implementation plan, for volume and biomass estimation methods would greatly add to the credibility of these estimates in the publicly available national FIA dataset.

Keywords: biomass equation, forest inventory, greenhouse gas inventory, FIA

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Introduction

The U.S. Forest Service, Forest Inventory and Analysis (FIA) program is receiving an ever-increasing number of requests for forest biomass and carbon estimates, in addition to the traditional volume estimates that have been central to the FIA program. Because the carbon content of wood and bark is about 50 percent of dry biomass (Houghton and others 1997), carbon estimates are obtained by multiplying dry biomass estimates by 0.5, and all discussion of carbon estimation focuses on the estimation of dry biomass. Previous analysis of the data in FIA's national database revealed inconsistencies in the biomass estimation approaches and resulting estimates in the FIA regions (for example, see Hansen 2002) suggesting that FIA needs a national approach to biomass estimation. More importantly, the standard prediction equations used nationally in conjunction with FIA tree measurement data to produce the official forest greenhouse gas (GHG) inventories of the United States (U.S. EPA 2008) are the biomass prediction equations developed by Jenkins and others (2003). Note that we use the phrase "biomass prediction equation" to indicate the equations are fitted models; the word "equation" alone implies an equality.

In addition to a relationship between biomass and carbon, it is logical to assume there should be a relationship between volume and biomass. This relationship is implicit in the biomass expansion factor (BEF) approach (Brown and others 1989, Houghton and others 1997, Somogyi and others 2007). The FIA program for years has developed and maintained a statistically sound, sample based inventory of forests of the United States, including estimated volumes of individual sample trees based on tree measurements applied to volume prediction equations. These prediction equations used by FIA, such as those described in Hahn and Hansen (1991) and Flewelling and Rayner (1993) have been developed specifically to obtain the best possible estimates of individual tree volumes on a regional basis, have received scientific peer review, and are being used extensively for volume estimation purposes. FIA volume estimation procedures take into account major species, diameter, and height, or other factors that help predict a tree's volume, as well as taking deductions for atypical tree form. Traditionally, FIA has focused on the estimation and reporting of net volume of wood in the bole (net means deductions for nonmerchantable portions of the bole are made); however, in recent years the focus has shifted to the estimation of sound volume where only deductions for missing and rotten portions of the bole are made. Tying biomass to sound volume, and then multiplying biomass by a carbon conversion factor, provides not only consistent volume and biomass estimates, but also 'matching' carbon estimates.

One way for FIA to calculate carbon estimates at this time in the national FIA databases is to simply adopt the Jenkins and others (2003) equations, arguably the current standard for carbon estimates in the United States (for example, see Smith and others 2006, U.S. Dept. of Energy 2006, U.S. EPA 2008). This would make the FIA database consistent with past national carbon reporting. It would not provide direct linkage between biomass and carbon estimates and the volume estimates.

The objective of this study is to conduct a preliminary analysis of a biomass expansion factor approach to investigate its potential to be a nationally consistent biomass computation procedure to calculate dry weight biomass in the publicly available national-level Forest Inventory & Analysis database, the FIADB (U.S. Forest Service 2008). Because "biomass expansion factor" is often used generically and consequently is ambiguous, we use the phrase "component ratio method" (CRM) to describe our BEF approach. We present the CRM approach in detail and apply it to a specific example as well as to all data from annualized surveys in the FIADB.

Background and Current Status

BEF and Forest GHG Inventories

FIA conducts statistically sound forest surveys over large areas (Bechtold and Patterson 2005). Measurements are taken, and prediction equations applied to calculate volume or biomass. Biomass may be calculated from measured tree attributes using biomass prediction equations, or calculated indirectly by multiplying the volume estimates by biomass factors that expand or convert the volume estimates to biomass. In the latter case, these factors are called "biomass expansion factors," originally applied only to expand stand-level volumes or volume growth. However, this phrase now has been applied generically at the tree level and has been used to mean a number of things, including converting units rather than factors that expand. See Somogyi and others (2007) for an extensive discussion of various definitions and facets of BEF approaches. A BEF approach is listed as the preferred method for some of the tiers in the Intergovernmental Panel on Climate Change guidance for national greenhouse gas inventories (Penman and others 2003). However, the higher tier methods call for greater specificity, such as country-level factors and factors specific to species. It is generally recognized that when individual tree data is available, biomass estimates based on individual trees are preferred.

A Standard Way to Develop Equations

The standard empirical way of developing credible biomass prediction equations is to collect data from a sample of trees across the range of sizes, from species and the area of interest. This approach was taken in Canada by Lambert and others (2005) and Ung and others (2008) using data from thousands of trees collected under the Energy from the FORest (ENFOR) project in the early 1980s. With these data, the authors could truly develop an internally consistent set of national allometric equations, including validation and testing. Two sets of equations were developed: one based on diameter at breast height (d.b.h) only and the other based on d.b.h and height. Such an approach provides not only predictions of individual tree biomass but also estimates of the bias and random error associated with these prediction equations.

A second credible approach is to collect unrelated datasets for a wide-ranging, well studied species without having to collect additional samples, and reanalyze the data. For instance, Wirth and others (2004) studied Norway spruce using this approach. Out of 688 trees, only 78 were completely sampled for biomass, and young trees especially were under-represented. In spite of this limitation, this study features important points to consider when designing a study to derive biomass equations. The credibility of the equations and estimates are strengthened by setting evaluation criteria on the process and resulting equations. This is discussed below.

Evaluation Criteria

Quality, science-based information for land management, at the strategic to applied level, is needed (USDA FS 2007). “Science-based” typically implies some type of peer-review, either as peer-review in journal publications or as a review by a designated panel of experts. The most stringent criteria for choosing participants in peer-review are for highly influential scientific assessments (OMB 2004), but even this document notes that different types of peer review are appropriate for different information. The Forest Survey Handbook[4] calls for “high quality, consistent and reliable data” in FIA databases, but provides little guidance on how to do that. More detailed guidance is given within the Forest Service Research and Development quality assurance program. Acceptance and publication in a peer-reviewed research journal is often an acceptable standard, but for highly influential work or in which the turnaround time is critical, expert panels are often preferred.

In the past, for individual studies, evaluation criteria for carbon accounting studies focused on criteria of accuracy, precision, consistency over time, and transparency, yet would also be cost-effective and usable by other scientists and managers and. Having a consistent approach over time is absolutely critical because it is the change in carbon over time, not just carbon stocks, which is of most interest in the terms of the carbon issue. Inconsistent approaches over time can affect the amount claimed to be sequestered. In this preliminary investigation, we do not formally evaluate the equations, but note issues and results to consider.

As new information needs and science results become available, it is important to re-evaluate existing systems, in this instance, equations, and consider adopting new approaches. To maintain consistency over time when implementing an “improved prediction equation” it is important to be able to apply the new method to not only current data but also to all previous data that form the historical record, to recode all tools that use the method being updated, and to work with

[4] Forest Service Handbook 4809.11 Amendment No. 4809.11-2001-1, approved 12/28/2008.

users to again develop credibility in the methods. Thus, changing estimation techniques is costly in many ways, and therefore changes are not undertaken without clear benefits.

Carbon Estimation in Forest GHG Inventories of the United States

The Jenkins and others (2003) biomass prediction equations are one of the pillars of the carbon estimates used for forests in the official greenhouse gas inventories of the United States (U.S. EPA 2008), which have arguably served as the "gold standard" for carbon. Scientific studies (for example, Potter and others 2008) compare their carbon results to carbon estimates based on the application of Jenkins and others (2003) to the FIA data, or use the estimates to calibrate their models. Virtually all the policy-relevant carbon estimates and carbon tools, such as the U.S. Greenhouse Gas Inventories (for example, U.S. EPA 2008, USDA 2008), Heinz Center carbon storage indicators (Heinz Center 2002, 2005, 2008), carbon indicators for the 2010 Sustainable Forests, the updated 1605b Voluntary Reporting Program of the United States (Smith and others 2006, Pearson and others 2008, U.S. Dept of Energy 2006, NCASI 2008); Carbon Calculation Tool (Smith and others 2007); Hoover and Rebain 2008 (FVS-Carbon) in the United States are based to at least some degree on FIA data and the biomass equations from Jenkins and others (2003). There are a number of studies that have used FIA regional biomass estimates for carbon (such as Schroeder and others 1997), but these studies only covered only a part of the conterminous United States.

Carbon estimates for trees based on databases of older plot-level FIA data are based on Smith and others (2003), which were developed based on biomass from Jenkins and others (2003). The Jenkins and others (2003) equations were developed at the time specifically because 1) large differences in tree biomass carbon between FIA units[5] for the same species and size tree sometimes occurred; 2) documentation for existing equations was scattered and uneven in its quality so it was difficult to check the data or know the source of the estimate; and 3) databases at the time did not include mass for standing dead trees. Some of these items are still true. Perhaps most importantly, forest carbon inventories were still viewed with some suspicion by many communities as highly uncertain, and having a method based on a peer-reviewed publication provided credibility, especially with carbon becoming a commodity in the marketplace.

Jenkins and others (2003) features 10 equations covering all tree species in the conterminous United States, based on a meta-analysis of a thorough compilation of all biomass equations (Jenkins and others 2004) found in the literature. These equations are based on diameter only because the databases available at that time included tree diameter in all tree records, but only occasionally included measured height (that is, not estimated from diameter). A similar approach was also

[5] The FIA units are designated by Northern Research Station (NRS), Pacific Northwest Research Station (PNWRS), Rocky Mountain Research Station (RMRS), and Southern Research Station (SRS).

adopted by Muukkonen (2007) to develop generalized allometric volume and biomass equations for some species in Europe for regional analyses, also based on diameter. Moreover, Muukkonen (2007) included equations with height in the underlying compilation of equations by using diameter-height equations, which is usually a strong relationship.

Some users of Jenkins and others (2003) equations have reported the equations estimate greater biomass than they expect at large diameters because height is not included, that the form of the equation forces biomass to continue to increase as diameter increases (see Figure 1). Users expect the rate of increase at larger diameters to be smaller with total biomass in a tree approaching some maximum upper limit rather than continuing to increase at an increasing rate. This issue may be worth revisiting.

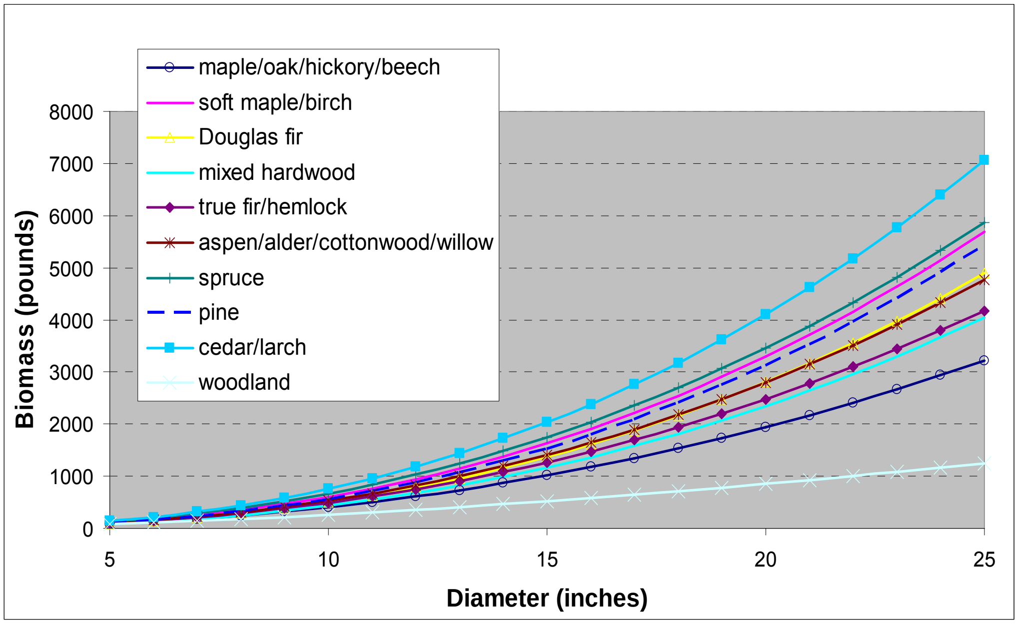

Figure 1: Total aboveground biomass from Jenkins and others (2003) estimated for each of the species groups. Note the diameter of woodland species may be measured at diameter root collar because some woodland species are multi-stemmed; this woodland equation is based on d.b.h.

FIA Biomass and Volume Estimation for Forests of the United States

There is currently no single publication that lists the tree biomass estimation approaches for all the FIA units. Current FIA biomass and volume equations have different forms for the regional FIA units, and were developed at different times from different datasets (Hansen 2002). Hansen (2002) documented the different volume and biomass estimation procedures in the eastern FIA units, which, due to historical reasons, included three sets of approaches for the current Northern Research Station (NRS) FIA alone. Methods were compared for 67 species that cross regional boundaries. Based on the results, Hansen cautioned users of FIA data from making regional comparisons of volume or biomass estimates for small diameter trees. He suggested that FIA needs to move to a consistent method to estimate tree volume and biomass nationwide that uses common measurement data. However, he also noted that consistency over time is an important consideration in revising equations because these will affect the calculation of changes over time.

Methods

Our approach entails compiling species-level wood densities (dry mass per unit green volume) to multiply by green bole volume for a dry biomass estimate per bole. This approach makes the biomass estimate for the bole portion of the tree equivalent to the FIA volume of that portion; adopting the Jenkins and others (2003) equations would not. In addition to tree biomass prediction equations, Jenkins and others (2003) presents equations to predict the proportion of the biomass in foliage; tops, limbs, and stumps; bark of bole; bole wood; and coarse roots; to the total aboveground biomass, respectively, for hardwood and softwood species by d.b.h. We use ratios developed from the component equations in Jenkins and others (2003) for a consistent approach to predicting biomass in other components of the tree besides the bole. We calculate the component ratio estimates based on the equation sets from Jenkins and others (2003), and produce proportions of tops and limbs, and root components in terms of bole wood biomass. The calculation of stump and bark components that the ratios are built from are based on different methods described below. We multiply these ratios in terms of bole biomass by our calculated bole biomass to calculate the biomass in each component pool.

Understanding the concepts underlying the current approaches is necessary to devise a method to calculate biomass from volume. First we define types of volumes and biomass used by FIA. We then briefly discuss current regional biomass computation. Finally, we describe the steps we used to calculate biomass from sound volume.

Definitions

Definitions of the various volume, biomass, and carbon components are key. FIA volumes are green wood basis—that is, they represent the volume of wood as standing or freshly cut, not the volume of dry wood, and bark is not included. The unit of measure of interest for this study is cubic feet, although other units of volume, such as board foot, are available from FIA. Volume is defined for trees greater than 5 inches diameter, and only includes the central bole of the tree from 1 foot aboveground to the point where the central stem has a diameter outside bark of 4 inches (or the point where the tree forks into branches all of which are less than 4 inches). This is the standard volume that has been used historically in most volume studies in the United States for more than 100 years. Trees less than 5 inches d.b.h., called saplings, are assumed to have zero volume.

Users of biomass equations and estimates in general need to aware that these may be on a dry or green weight basis; may include or exclude bark, foliage, stump and root portions of trees; may include seedlings (trees < 1 inch diameter); or may include species that FIA considers to be shrubs rather then trees. Also the units of measure for reporting biomass include pounds, tons and kilograms. Biomass in this study is on an oven-dry basis and includes bark, but excludes foliage. The unit of measure is pounds unless otherwise noted and FIA biomass is defined only for trees greater than 1-inch diameter. FIA biomass estimates typically include only the aboveground portion, however, with the introduction of FIADB4 a prediction of the biomass in the coarse roots portion of all trees greater than 1-inch diameter has been added.

Volume

FIA defines and calculates gross, sound, and net bole volumes, of all live trees at least 5 inches d.b.h (USDA FS 2008b) (Fig. 2). These volumes are estimated for the central stem (bole) from a 1-foot stump to a minimum 4-inch top diameter outside bark, or to a point where the central stem breaks into limbs. The only time there are differences between these three volume estimates for a tree is when the estimated rotten or missing parts of the tree are nonzero, or when the tree has poor form. Gross volume is the total potential volume; rotten or missing parts of the tree and poor form effects on tree volume have not been deducted from gross volumes. Sound volume is gross volume with missing and rotten volumes of the tree deducted. Net volume is gross volume minus deductions for rot, roughness, and poor form. Depending on the FIA unit, either gross volume or net volume will be calculated first, as well as the missing and rotten, or volume affected by form, and then sound volume is calculated by adding or subtracting the appropriate portion. Many of the gross volume prediction equations used by the Pacific Northwest Research Station FIA unit are based on the integration of taper equations that predict the diameter of the bole at any height, such as those in Flewelling and Rayner (1993). The Northern Research Station FIA unit is in the process of converting its volume estimation to a taper equation-based system. These taper-based systems are capable of predicting the bole volume in any portion of the bole from the ground to the top of the tree.

Biomass

FIADB3 (version 3 of FIADB) includes two biomass variables: total gross (named DRYBIOT in the database) and merchantable stem (DRYBIOM) biomass. Total gross aboveground biomass includes main stem, bark, tops, limbs and stump of all live trees 1 inch in diameter or larger, but excludes foliage and roots. Merchantable stem biomass includes only trees greater than or equal to 5 inches d.b.h from a 1-foot stump to a minimum 4-inch top outside bark of the central stem. All trees less than 5 inches d.b.h have total biomass, but they have a merchantable biomass of zero. Gross biomass minus merchantable biomass produces the amount of biomass in tops, limbs, and stumps, as well as all the biomass in trees less than 5 inches diameter. See Figure 3 for an illustration of the differences between these types of biomass.

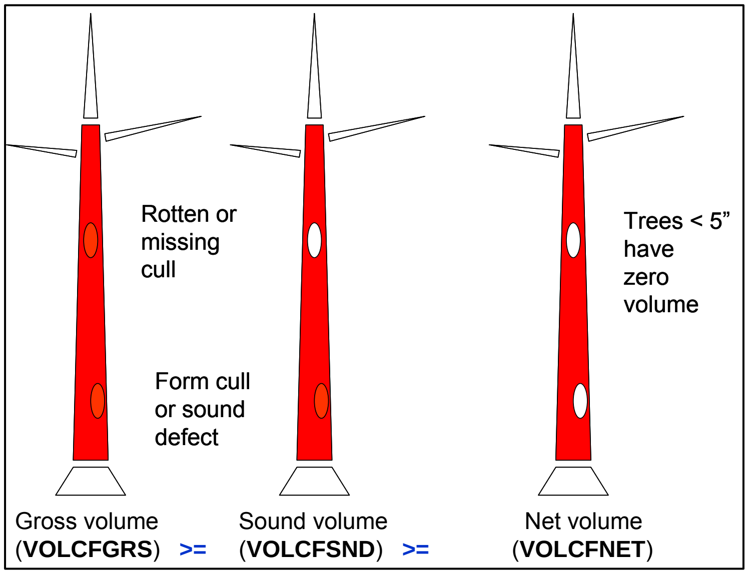

Figure 2: Illustration of gross, sound, and net volume at the tree-level.

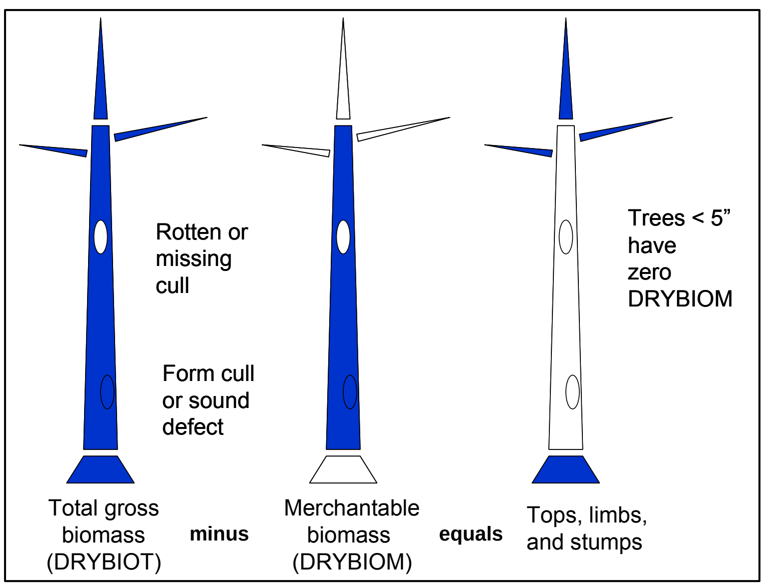

Figure 3: The difference between gross and merchantable biomass as stored in FIADB3.

The components of biomass in this approach are illustrated in Figure 4. The biomass components for top and limbs (labeled DRYBIO_TOP) are broken out from the stumps (DRYBIO_STUMP) and the merchantable (bole) biomass has been labeled DRYBIO_BOLE because it is not the same value as in previous FIA datasets. These three variables are computed for all species where FIA measured d.b.h., and are defined to be zero for woodland tree species (because diameter is measured at root collar) and for trees less than 5 inches d.b.h. To avoid confusion, the attributes DRYBIO_SAPLING (total aboveground biomass in trees 1 to 5 inches d.b.h) and DRYBIO_WDLD_SPP (total aboveground biomass in woodland species) have been added. Belowground biomass estimates in coarse roots are not part of FIADB3; however, these estimates are of interest and are shown in the illustration as DRYBIO_BG.

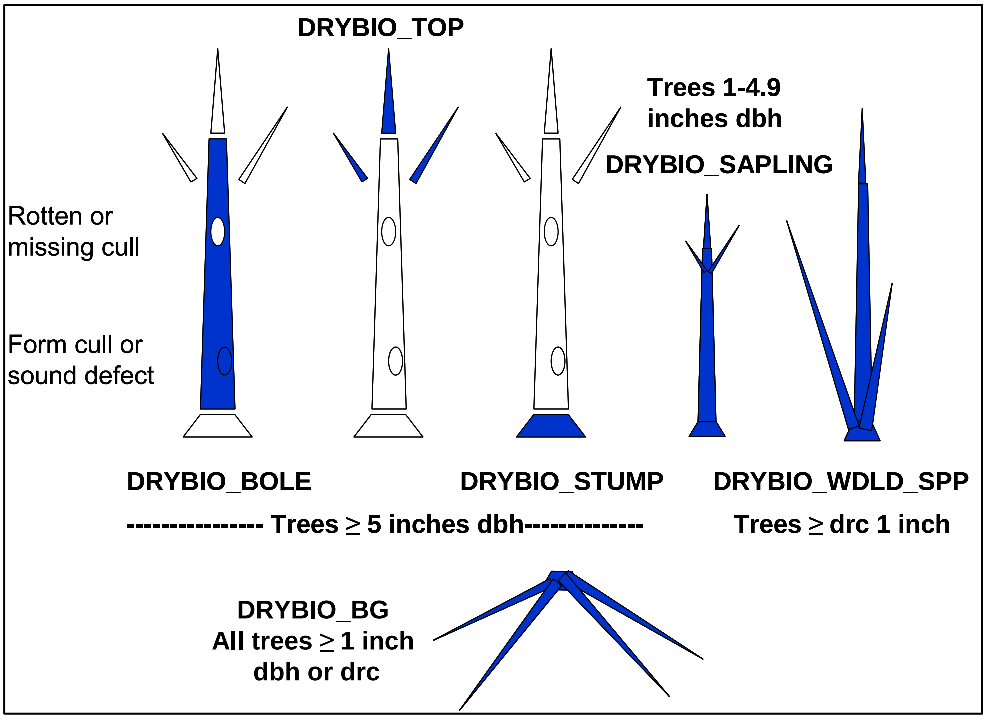

Figure 4: Biomass variables needed to implement this method in the FIADB.

Inconsistencies in estimation of component biomass

FIA biomass estimation procedures have shown unexpected differences in the average amount of biomass in tops, limbs, and stumps. Table 1 shows an example of the differences between eastern FIA units using select red oak trees of 10 inches d.b.h and 60-70 feet in height from all trees measured over the period 1999-2006, using regional equations and the Jenkins and others (2003) equations. The percent in tops, limbs, and stumps varies from approximately 10 to 30 percent in the eastern units, based on the current biomass calculation procedures. The pounds of wood per cubic foot of sound wood vary from 40 lbs/cu ft to almost 54 lbs/cu ft. The region with the higher lbs/cu ft has the lowest percentage in tops, limbs, and stumps. A revised approach should result in these components being similar between regions.

Table 1: Biomass statistics for all 10-inch diameter at breast height, select red oak growing stock trees, 60-70 feet tall, from all FIADB3 observations, 1999-2006.

FIA Region[a]	DRYBIOM/VOLCFSND	(DRYBIOT-DRYBIOM)/DRYBIOT
	--Pounds wood and bark per cu ft sound wood--	*--Percent of total biomass in tops, limbs, and stumps--*
Using regional equations:		
NRS-East	53.5	11.3
NRS-West	40.9	29.8
SRS	41.4	21.8
Using Jenkins and others (2003):		
NRS-East	40.7	26.5
NRS-West	47.7	26.5
SRS	38.3	26.5

[a] NRS-East: the eastern portion of the Northern Research Station which is the area covered by the former Northeastern Research Station, NRS-West: the western portion of the Northern Research Station which is the area covered by the former North Central Research Station, and SRS: Southern Research Station..

Component Ratio Method (CRM)

For trees 5 inches in diameter and greater, total aboveground biomass is computed as the sum of three components: bole of the tree, tops and limbs, and the stump. Bole biomass is the largest portion of aboveground biomass. Stumps, tops and limbs, and saplings are a significant yet much smaller portion of the total aboveground biomass in most forests. The biomass of saplings, that is, trees less than 5 inches in diameter but greater than or equal to 1-inch diameter, are based on an adjustment of Jenkins and others (2003) equations because they have zero volume. Belowground biomass, that is, biomass of coarse roots, is predicted as a ratio of aboveground tree biomass. We present the details of these calculations by section below.

Aboveground Biomass of Trees ≥ 5 inches d.b.h., Dry Weight: Total aboveground biomass (dry weight) of trees greater than or equal to 5 inches d.b.h. is calculated as the sum of three components of the tree:

$$\text{AGBIOT5} = \text{DRYBIO\_BOLE} + \text{DRYBIO\_STUMP} + \text{DRYBIO\_TOP} \quad [1]$$

where AGBIOT5 (lbs) = total aboveground biomass (dry weight), including bark but excluding foliage, of a tree ≥ 5 inches d.b.h.,

DRYBIO_BOLE (lbs) = biomass (dry weight, including wood and bark) of the main stem of tree that also defines sound volume,

DRYBIO_TOP (lbs) = biomass of top and limbs (dry weight, excluding foliage but including bark) of trees ≥ 5 inches d.b.h., and,

DRYBIO_STUMP (lbs) = biomass (dry weight) of wood and bark from ground level to 1 foot stump.

Biomass of the Bole: Biomass of the bole of a particular species is calculated by multiplying green volume (cu ft) by the weight of one cubic foot of water (62.4 lbs/cu ft) to convert to a weight basis, and then multiplying by the specific gravity of the component, including wood and bark, separately, for that species. Specific gravities are obtained by laboratory studies, and the results compiled by species where available, or assigned to similar species. Here, specific gravities in terms of dry weight per unit of green volume are used. Because the specific gravity is different for bark and wood, these two components are calculated separately and then summed. The calculation for bark has an additional term, bark as a proportion of wood volume. Bark volume in terms of percentage is given in Table 2; proportions are equal to percent divided by 100. Specific gravities used in this study are from Miles and Smith,[6] which build on the compilations by Smith (1991) and Jenkins and others (2004).

DRYBIO_BOLE (lbs) = (VOLCFSND x 62.4 x SG_BARK x BRK_VOL_PROP) + (VOLCFSND x 62.4 X SG_WOOD) [2]

with DRYBIO_BOLE (lbs) = biomass (dry weight, including wood and bark) of the main stem of tree that also defines sound green volume (VOLCFSND),

VOLCFSND (cu ft) = sound green wood volume of a tree ≥ 5 inches d.b.h.,

SG_BARK = dry weight specific gravity of green bark volume of tree bole,

BRK_VOL_PROP = ratio of green volume of bark to green volume of sound wood (see Table 2), and,

SG_WOOD = dry weight specific gravity of green wood volume of tree bole.

Table 2: Bark as a percent of wood volume by Jenkins and others (2003) species groups.

Jenkins groups[a]	(Bark as % of wood volume)	Jenkins groups[a]	(Bark as % of wood volume)
Aspen/alder/ cottonwood/willow	20	Cedar/larch	15
Soft maple/birch	14	Douglas-fir	14
Mixed hardwood	18	Pine	18
Hard maple/oak/ hickory/beech	19	Spruce	12
Woodland	12	True fir/hemlock	15

[a]Exceptions to these species groups are coastal redwood, giant sequoia, baldcypress, eastern, western, and Carolina hemlock – 25%; beech, sycamore – 7%

Factors for Calculating Top & Limbs and Stump Biomass: The biomass in the stumps and tops and limbs of large trees make up the next largest components of aboveground biomass in most forests. Jenkins and others (2003) provide equations that calculate total aboveground biomass, and also a set of equations that estimate the proportion of biomass in the tops and limbs as well as other tree components. The CRM uses the component equations from Jenkins and others (2003) to compute the ratio of the component to Jenkins total aboveground biomass. These ratios are then multiplied by the bole biomass calculated in [2] using the CRM approach to produce the biomass in tops and limbs (DRYBIO_TOP), and biomass of the stump (DRYBIO_STUMP). We cannot apply those equations directly because the value of our biomass bole is not the same.

[6] Miles, Patrick, and W.B Smith. In review. Wood and bark specific gravity for tree species in the continental United States. USDA Forest Service, Northern Research Station. Research Note.

Applying these component ratios to biomass equations other than Jenkins and others (2003) results in different absolute biomass estimates than would be produced by Jenkins and others (2003). However, we assume that the proportions are the same, and thus we calculate these factors to multiply by our bole biomass. Equation 3 shows the formula for calculating the proportion in tops and limbs. Stump biomass in Jenkins and others (2003) is based on stump volume equations from Raile (1982). Equations 4 and 5, respectively, show the computations for factors related to stumps.

TPLMB_PROP = ((BIO_TOP_JENKINS)/(DRYBIO_BOLE_JENKINS)) [3]

where TPLMB_PROP = proportion of bole biomass that is biomass in top and limbs,
BIO_TOP_JENKINS (kg) = biomass in top and limbs using Jenkins, and,
DRYBIO_BOLE_JENKINS (kg) = biomass of the bole based on Jenkins.

DRYBIO_STUMP_RAILE (kg) = d.b.h (inch)*d.b.h (inch)*ParameterB [4]
where DRYBIO_STUMP_RAILE (kg) = stump biomass, and,
Parameter B = coefficient from Table 1 in Raile (1982).

STUMP_PROP = ((DRYBIO_STUMP_RAILE(kg)) /(DRYBIO_BOLE_JENKINS(kg))) [5]
where STUMP_PROP = proportion of bole that is stump biomass,
DRYBIO_STUMP_RAILE (kg) = biomass in stump, and,
DRYBIO_BOLE_JENKINS (kg) = biomass of the bole using Jenkins.

Top and Limb Biomass: Equation 6 shows the computation for estimating biomass in the top and limbs.

DRYBIO_TOP = DRYBIO_BOLE x TPLMB_PROP [6]

where DRYBIO_TOP (lbs) = biomass of top and limbs (dry weight, excluding foliage but including bark) of trees ≥ 5 inches d.b.h., and,
DRYBIO_BOLE (lbs) = biomass (dry weight, including wood and bark) of the main stem of tree that also defines sound volume (VOLCFSND), and,
TPLMB_PROP = proportion of bole biomass that is biomass in top-limbs.

Stump Biomass: Equation 7 shows the computation for stump biomass.

DRYBIO_STUMP = DRYBIO_BOLE x STUMP_PROP [7]
where DRYBIO_STUMP (lbs) = biomass (dry weight) of wood and bark from ground to 1 foot stump,
DRYBIO_BOLE (lbs) = biomass (dry weight, including wood and bark) of the main stem of tree that also defines sound volume, and,
STUMP_PROP = proportion of bole that is stump biomass, see above.

As FIA converts to a taper-based system to predict sound volume, it will be possible to directly calculate the sound wood volume in any section of the bole, including the stump. Thus, the separate stump calculation based on Raile (1982) will not be needed.

Aboveground Saplings: The biomass of saplings is based on biomass computed from Jenkins and others (2003) on the observed diameter multiplied by an adjustment factor. For the purposes of this preliminary investigation, the adjustment factor was computed as a national average ratio of the CRM total biomass divided by the Jenkins total biomass for all 5-inch trees, which is the size at which biomass based on volume begins. Each species group has an adjustment factor, which is given in Table 3. Computations are shown in Equation 8.

DRYBIO_SAPLING = (BIO_SAP_JENKINS - FOLIAGE) X (1- JENKINS_SAPLING_ADJUSTMENT)) [8]

with DRYBIO_SAPLING (lbs) = aboveground biomass of trees < 5 inches d.b.h and ≥ 1.0 inch d.b.h., including wood, bark, and stump, but excluding foliage,

BIO_SAP_JENKINS (lbs) = aboveground biomass calculated using Jenkins and others (2003), converted to pounds

FOLIAGE (lbs) = dry weight of foliage from Jenkins and others (2003) converted to pounds, needed to subtract off foliage,

JENKINS_SAPLING_ADJUSTMENT = factor that adjusts Jenkins biomass for trees < 5 inches d.b.h for a smooth transition at 5-inch trees (see Table 3).

As with the stump biomass (DRYBIO_STUMP), when taper equations are available for volume estimation in all FIA units, it will be possible to calculate the central stem component of sapling biomass if the taper equations have been fit to datasets that include an adequate sample of smaller trees. This may prove to provide a better prediction of biomass in sapling size trees.

Belowground (Root) Biomass: Equation 9 shows the computation for coarse root biomass.

DRYBIO_BG = DRYBIO_BOLE x ROOT_PROP [9]

where DRYBIO_BG (lbs) = biomass of coarse roots,

DRYBIO_BOLE (lbs) = as above,

ROOT_PROP = ((ROOT _JENKINS)/(DRYBIO_BOLE_JENKINS)), which is the proportion of bole biomass to biomass in coarse roots,

ROOT_JENKINS (kg) = biomass in roots calculated using Jenkins, and,

DRYBIO_BOLE_JENKINS (kg) = biomass of the bole based on Jenkins.

Table 3: Adjustment factors applied to Jenkins and others (2003) sapling equations for the component ratio method.

FIA species codes	Jenkins sapling adjustment	Common name
58-60,62,63,65,66,69,106,133,134,140,141,143	0.352	Juniper, pinyon
745,747-749	0.378	Cottonwood
211	0.410	Redwood
116,122,135	0.434	Ponderosa pine
92,93,96	0.442	Spruce
41,42,50-55,64,72,101-104, 109,112-114,118, 120,124, 127,137-139,142,201,212, 231,251, 264, 299	0.458	Pines, other conifers
98	0.463	Sitka spruce
202	0.526	Douglas-fir
117	0.557	Sugar pine
119	0.574	Western white
81	0.588	Incense-cedar
11,14,15,17-22	0.602	Fir
10,12,90,94,95,97	0.608	Balsam fir, spruce
260-262	0.628	Eastern hemlocks
16,40,43,56,57,61,67,68,70,71,91,100,136,144, 200, 220, 230,232,240,241,252	0.631	Various conifers
531	0.632	American beech
105	0.643	Jack pine
300,321,322,475,755-758, 803,810,814,829,843,846, 847,850,81,902,990	0.651	Variety, woodland species
263	0.671	Western hemlock
950-953	0.672	Basswood
740-744, 746,752,753	0.691	Cottonwood
242	0.705	Western redcedar
822,832,835,836,838,840, 841,844	0.722	Oaks
125,129	0.729	Red pine, white pine
400-413,316,317	0.744	Hickory, misc. maples
611	0.749	Sweetgum
351	0.750	Red alder
110,131	0.763	Shortleaf, loblolly pine
802,804,808,823,825,826	0.770	White oaks
801,805,807,811,815,818, 821,839	0.774	Western oaks
806,809,812,817,820,824,827,828,830,831,837	0.780	Black oaks
371	0.789	Yellow birch
313,331,332,334,337,350,355,370,373,375,377, 379,422,452,460-463,555,580-583,600,601,605, 650-653, 655,657,658,712,729,731,762,911, 912,915,922,924,927,928,929,931,970-976,992	0.792	Mixed hardwoods
73	0.800	Western larch
813,833,834	0.811	Oaks
All other species not listed elsewhere	0.840	All other species
310,311,314,318,320,323, 690, 691,693, 694	0.841	Maples, tupelo
621	0.852	Yellow-poplar
602	0.872	Black walnut
108	0.883	Lodgepole pine
111,121	0.922	Slash, longleaf pine
372,450,491,510,513,521, 550, 551,552, 571,591,680- 683,800,858,901,977	0.932	Various hardwoods
541,543-546,548,549	0.936	Ash
221-223	0.952	Taxodium
312,330,333,352,353,361-363,374,378,431,492,511, 542,547,603,604,606,631, 661,730,732,768,981	0.964	Various hardwoods
107,115,123,126,128,130, 132	1.011	Various pines

Example

We present an example for using Jenkins and others (2003) and CRM for estimating biomass for a 4-inch tree and 25-inch tree, red oaks in the NRS-East region. For the 25-inch CRM, we use the volume calculated in the FIADB because we do not have the volume equations readily available. Mass is in terms of dry weight.

Information needed for the Jenkins estimates:

- The species and d.b.h for the individual tree.
- Red oak, species code 833, is in the "hard maple/oak/hickory/beech" group (mo). Therefore the paired coefficients (b0,b1) needed for estimates are: (-2.0127, 2.4342) for total aboveground biomass, (-4.0813, 5.8816) for foliage, and (-1.6911, 0.816) for the coarse root component.
- Metric-English conversions for length and mass: 1 inch equals 2.54 centimeters, and 1 kilogram equals 2.2046 pounds.

For a 25-inch d.b.h tree excluding foliage, aboveground biomass is based on deducting foliage from the aboveground-biomass equation:

- Total aboveground biomass = exp(b0 + b1 × ln(d.b.h)) = exp(-2.0127 + 2.4342 × ln(25×2.54)) = 3267.4 kg dry weight = 3267.7 × 2.2046 = 7203.4 pounds.
- Foliage component ratio = exp(b0 + b1/d.b.h) = exp(-4.0813 + 5.8816/(25×2.54)) = 0.01852. Thus, foliage biomass (total × component) = 7203.4 × 0.01852 = 133.4 pounds.
- Therefore, the aboveground biomass excluding foliage for a 25-inch d.b.h tree is the difference: 7203.4 - 133.4 = 7070 pounds.

Similarly, for a 4-inch d.b.h tree

- Total aboveground biomass = exp(b0 + b1 × ln(d.b.h)) = exp(-2.0127 + 2.4342 × ln(4×2.54)) = 37.75 kg = 37.75 × 2.2046 = 83.22 pounds.
- Foliage component ratio = exp(b0 + b1/d.b.h) = exp(-4.0813 + 5.8816/(4×2.54)) = 0.03013. Thus, foliage biomass (total × component) = 83.22 × 0. 03013 = 2.507 pounds.
- Therefore, the aboveground biomass excluding foliage for a 4-inch d.b.h tree is the difference: 83.22 - 2.507 = 80.71 pounds.

Belowground, or coarse root, biomass for the 25- and 4-inch d.b.h trees are based on total aboveground biomass and the coarse root component:

- Coarse root component = exp(b0 + b1/d.b.h) = exp(-1.6911 + 0.816/(25×2.54) = 0.1867 for a 25-inch d.b.h tree and exp(-1.6911 + 0.816/(4×2.54) = 0.1997 for a 4-inch d.b.h tree.
- Therefore, the belowground biomass for a 25-inch d.b.h tree is the product: 7203.4 × 0.1867 = 1345 pounds.
- Therefore, the belowground dry weight for a 4-inch d.b.h tree is the product: 83.22 × 0.1997 = 16.62 pounds.

Information needed for the CRM estimates:

- The species and volume of sound wood (VOLCFSND) from the FIADB.
- The set of Jenkins biomass and component coefficients for red oak, as provided above plus the additional paired coefficients (b0,b1): (-2.0129, -1.6805) for the stem bark component, (-0.3065, -5.424) for the stem wood component, and (-1.6911, 0.816) for the coarse root component.
- Five additional species-specific factors: (1) the ratio of volume of bark to volume of wood (aka BARK_VOLUME_PROP); (2) specific gravity of wood (aka SG_WOOD); (3) specific gravity of bark (aka SG_BARK); (4) a factor for estimating stump biomass based on Raile (1982, aka RAILE_STUMP_B1); (5) an adjustment factor applicable to trees less than 5 inches d.b.h (JENKINS_SAPLING_ADJUSTMENT).
- Most calculations are in English units. However, the metric-to-English conversion of 1 kg equals 2.2046 pounds may be necessary if stump biomass units are in pounds. The density of water is 62.4 pounds per cubic foot.

For a 25-inch d.b.h tree excluding foliage, aboveground biomass is based on determining merchantable biomass and then expanding according to the top and stump component ratios:

- Merchantable biomass, or biomass of the bole = VOLCFSND × (BARK_VOLUME_PROP × SG_BARK × density of water) + VOLCFSND × (SG_WOOD × density of water) = 103.04 × (0.19 × 0.65 × 62.4) + 103.04 × (0.56 × 62.4) = 794.07 + 3600.63 = 4394.8 pounds.
- Note that volume equations are needed, as well as information on defects and form to calculate sound volume; we do not include that here as this information is not readily available.
- Top component ratio = (Jenkins total aboveground – Jenkins merchantable – Raile stump – Jenkins foliage) / (Jenkins merchantable) = (7203.4 - 5805.0 – 176.3 - 133.4) / (5805.0) = 0.1875.
  - o Where Jenkins merchantable = (Jenkins total aboveground) × (Jenkins stem bark component + Jenkins wood component) = (7203.4) × (exp(-2.0129 + -1.6805/(25×2.54)) + exp(-0.3065 + -5.424/(25×2.54))) = 7203.4 × (0.1301 + 0.6758) = 7203.4 × 0.8059 = 5805.0 pounds.
  - o Where Raile stump = DIA × DIA × RAILE_STUMP_B1 = 25×25 × 0.12798 = 79.99 kg x 2.2046 lbs/kg = 176.3 pounds.
- Stump component ratio = Raile stump / Jenkins merchantable = 80.0 / 5805.0 = 0.03038.
- Therefore, the aboveground biomass excluding foliage for a 25-inch d.b.h tree is = 4394.8 × (1 + top component ratio + stump component ratio) = 4394.8 × (1 + 0.1875 + 0.03038) = 5352.3 pounds.

Aboveground biomass, excluding foliage, for a 4-inch d.b.h tree = Jenkins aboveground biomass without foliage × JENKINS_SAPLING_ADJUSTMENT = 80.71 × 0.81068 = 65.43 pounds.

Belowground, or coarse root, biomass for the 25-inch d.b.h tree is based on merchantable biomass and the coarse root component ratio:

- Coarse root component ratio = (Jenkins coarse root) / (Jenkins merchantable) = 1344.9 / 5805.0 = 0.2317.
- Therefore, the belowground biomass for a 25-inch d.b.h tree is the product: 4394.8 × 0.2317 = 1018 pounds.

Belowground, or coarse root, biomass for a 4-inch d.b.h tree = Jenkins belowground biomass × JENKINS_SAPLING_ADJUSTMENT = 16.62 × 0.81068 = 13.47 pounds.

Results and Discussion

This approach was applied to all trees in all the annualized surveys in the FIABD3, using a preliminary set of specific gravities by species. In terms of merchantable biomass and percent in tops, limbs, and stumps, results in Table 4 indicate that the larger differences in Table 1 have been resolved. Figure 5 also indicates that other problems with tops, limbs, and stump can be resolved using the CRM approach. In particular, the regional percentages for PNWRS-softwoods and NRS-East hardwoods are quite different compared to the other regions, but the CRM-based results are more similar among units. The range in average top, limbs, and stump by unit is about 10 to 33 percent using the regional approaches, but the range is 16 (PNWRS-softwoods) to 27 (RMRS – hardwoods) percent using CRM. These results conform to what is expected given the nature of the predicted tops and limbs proportions (TPLMB_PROP) from Jenkins and others (2003) which predict the smallest proportions for large diameter softwoods and the largest proportions for small diameter hardwoods. The PNWRS has the largest average diameter of softwoods and the RMRS region has the smallest average diameter of hardwoods.

Table 4: Select red oak, 10-inch d.b.h., 60-70’ height, growing stock trees,—CRM equations.

FIA region[a]	DRYBIOM/VOLCFSND	DRYBIOT-DRYBIOM/DRYBIOT
	--Pounds wood and bark per cubic feet of sound wood--	*--Percent of total biomass in tops, limbs, and stumps--*
NRS-East	42.7	26.5
NRS-West	42.7	26.5
SRS	43.6	26.5

[a] NRS-East: the eastern portion of the Northern Research Station which is the area covered by the former Northeastern Research Station, NRS-West: the western portion of the Northern Research Station which is the area covered by the former North Central Research Station, and SRS: Southern Research Station.

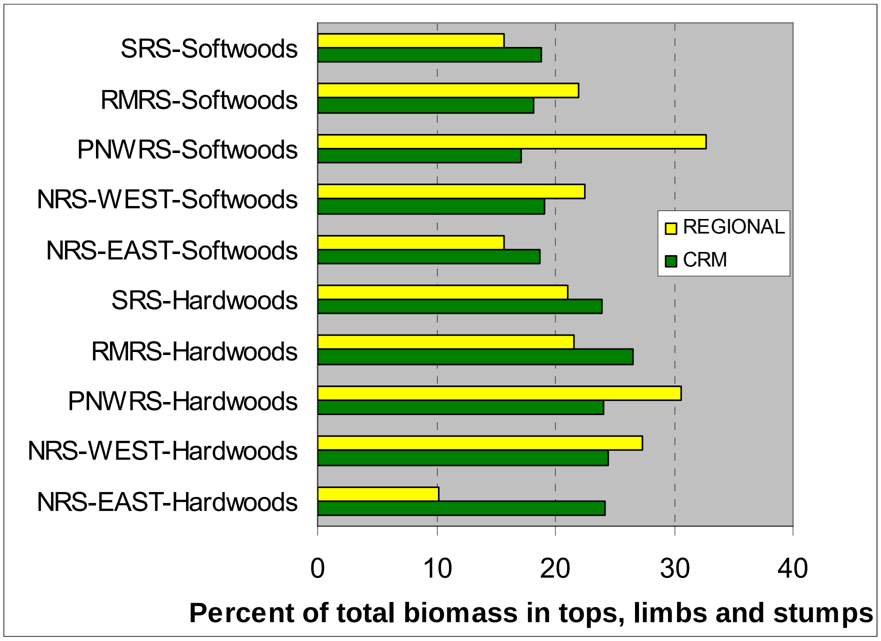

Figure 5: Percent of live tree biomass of all forest land trees ≥ 5 inches d.b.h. in tops, limbs, and stumps for the current regional approach and the proposed CRM, by softwood/hardwood and FIA unit. Abbreviations for unit designations are: SRS = Southern Research Station, RMRS = Rocky Mountain Research Station, PNWRS = Pacific Northwest Research Station, NRS = Northern Research Station where NRS-East = the former Northeastern Research Station and NRS-West = the former North Central Research Station. Note: This figure currently includes component ratios of woodland species; however, woodland species were not included in the Jenkins and others (2003) calculation of component ratios.

Figure 6 shows the overall effect that implementing either the CRM or Jenkins and others (2003) on a national basis would have on the total estimated biomass in trees 5 inches diameter and larger within each of the regions. Aboveground biomass estimates for trees ≥ 5 inches d.b.h on a tons per acre basis from Jenkins and others (2003) tend to be greater than estimates from the other approaches. The current regional approach for NRS-East is a compilation of biomass equations, including some that were used in the development of Jenkins and others (2003). The biomass prediction methods in NRS-West, RMRS and for many species in PNWRS[7] are based on volume predictions and are therefore very similar to the CRM. Thus, the CRM estimates in these regions are quite close to the regional estimates. The CRM approach reduces biomass densities even further compared to the current regional equations, with the exception of

[7] For example, for PNWRS, bole wood volume is predicted based on species, diameter, and height measurements, and a library of volume equations specific to the species or species groups and portion of region. These equations take on different forms, but many are based on the integration of taper equations such as Flewelling and Raynes (1993). Bole bark volume is computed from a variety of sources including methods that calculate inside bark and outside bark volume using equations from Pillsbury and Kirkley (1984). These are then multiplied by wood weight to get bark mass. These bole wood and bole bark volume predictions are converted to biomass using specific gravity estimates, many of which are in Table 3. Branch, top, and stump mass calculations come from a variety of sources, such as Snell and others (1983), Gholz and others (1979), and Cochran and others (1994). These components are added to obtain predictions of total aboveground biomass.

estimates for RMRS which are only slightly greater on a per acre basis. Note we are not presenting any validation evidence to prove that the CRM-based estimates are any more accurate than the regional estimates or Jenkins and others (2003).

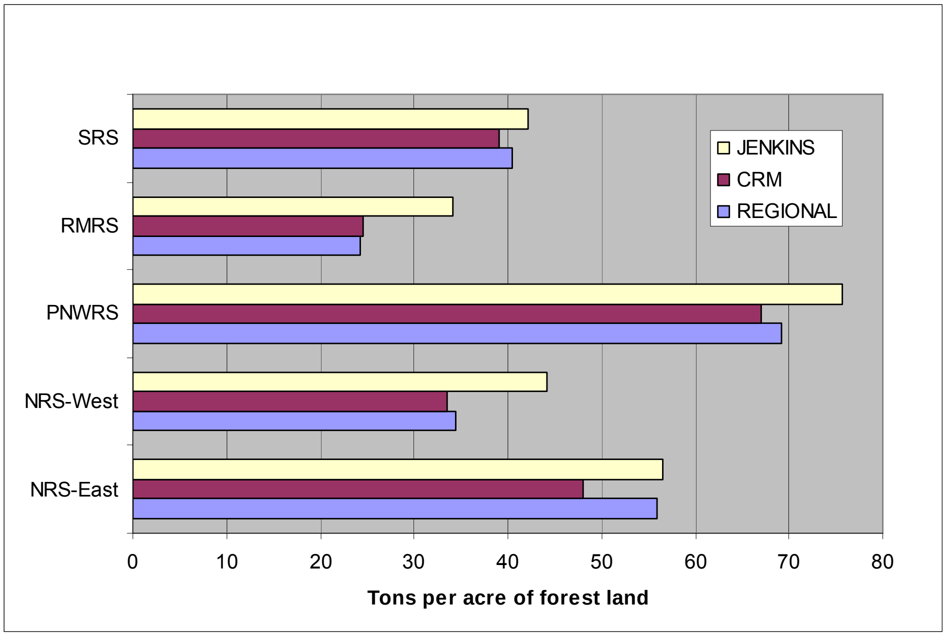

Figure 6: Aboveground live tree biomass per acre by approach by FIA unit, all trees ≥ 5 inch, conterminous United States.

In this preliminary investigation, we have not examined how the different equations affect change in biomass over time. If the older estimates are not updated, we will be comparing a smaller estimate based on the CRM method to a larger estimate from an older method. Even if the tree did not change in size, the trees would show a notable artificial loss in biomass if a new method were adopted before the older estimates could be updated.

The measurement of change in volume over time and the breakdown of this change into various components of change such as growth, removals and mortality has been a central part of FIA estimation. To produce these estimates it is vital that both old and new observations are based on the same prediction methods. Whenever a new volume estimation procedure is implemented in FIA, there has been a need to recalculate previous inventory methods. A volume based system such as CRM facilitates recalculations of biomass and the computation of biomass change into the standard FIA data processing system. Similarly, carbon change has been central in the GHG inventory estimates and the use of Jenkins and others (2003) equations. It is absolutely crucial to recalculate all the biomass data going back in time to ensure the change over time for biomass and carbon sequestration calculations is not simply due to a change in equations.

Figure 7 shows a comparison of Jenkins and others (2003) in terms of average total aboveground biomass by d.b.h. with both the FIA regional and CRM methods for only one species group, alder/aspen/willow/cottonwood. This is probably the most wide-ranging group, growing throughout the conterminous United States. In the NRS-West, PNWRS, and RMRS regions the CRM and regional methods produce very similar results to the CRM. In those regions the regional method is based on bole volume, rather than on independent biomass equations as it is in NRS-East and SRS. The results from various FIA units bound the results from the Jenkins and others (2003) equations, illustrating how those equations effectively yield an average estimate composited from published equations across the United States. Note that differences in these results could be due to different equations used in the different regions, tree size, number of trees, and different species mix.

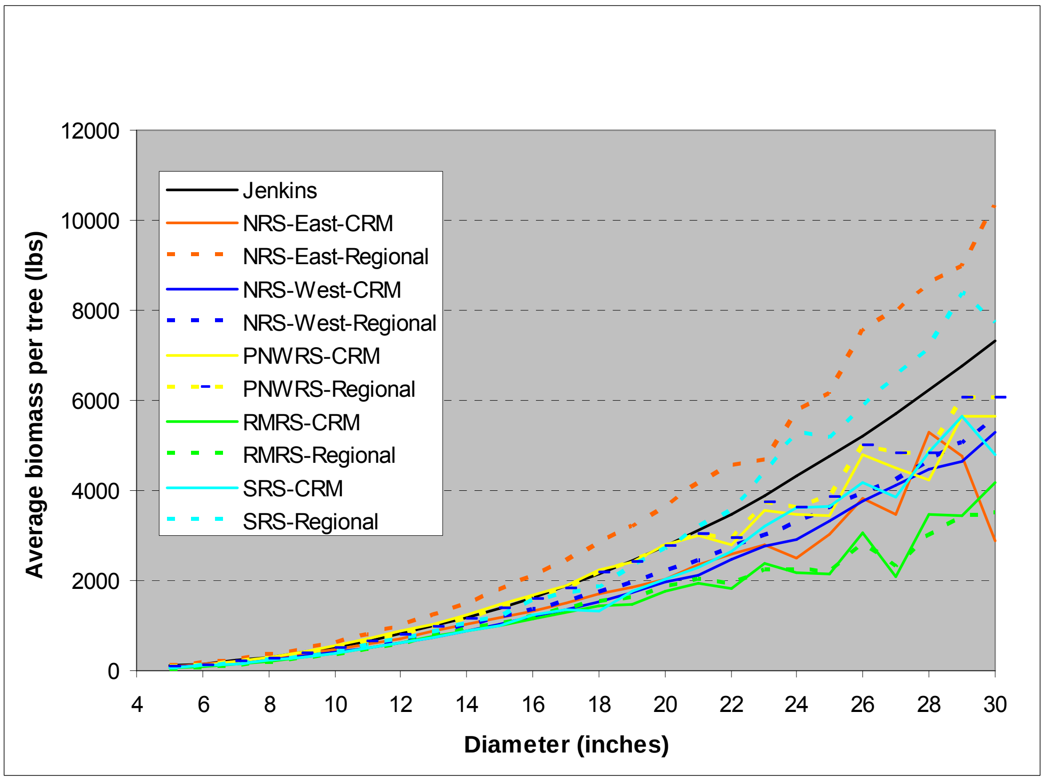

Figure 7: Average aboveground tree biomass for each FIA region based on both the current FIA regional and CRM methods by diameter, and the aboveground tree biomass from the Jenkins and others (2003) equation for the alder/aspen/willow/cottonwood species group. For the regional and CRM methods, all tree data of alder/aspen/willow cottonwood species from 137,701 trees (NRS-EAST 10,507 trees, NRS-WEST 81,812 trees, PNWRS 9,558, RMRS 31,498, and SRS 4,326) in FIADB3 from annualized surveys are used (biomass in lbs; diameter in inches)

Comparing Jenkins and others (2003) with the CRM approach, as shown in Figure 7, estimates from all the units are less than those from Jenkins and others (2003). Note that differences in these results could be due to different volume equations, which are the basis for the CRM, used in the different regions, tree size, number of trees, and different species mix. Although densities of wood and bark do not change at FIA unit boundaries, volume equations do (Hansen 2002), and since biomass based on CRM is based on volume equations, biomass estimation still changes at FIA unit boundaries.

Several items in the CRM were identified in this preliminary investigation as needing further work to meet the Forest Survey Handbook standard of "high quality, consistent and reliable data." Component ratios for woodland species need to be derived. Stump equations need to be reworked to match specific gravity and bark estimates from the tables. The adjustment process to the Jenkins and others (2003) biomass predictions for use in CRM for diameters less than 5 inches needs further consideration. The implementation of a well designed national system for bole volume prediction that is based on taper equations would address these issues. Datasets for validation should be compiled, at least for major species to test the accuracy of the equations. For transparency, a full well-documented compilation of volume equations is needed for all FIA units and species. A complete set of specific gravities by species, well-documented and consistent with existing estimates in the published literature is needed. Such documentation will also meet the needs of users of FIA data, who sometimes collect their own inventory data, and would like to apply the same compilation procedures as FIA so they can compare their biomass and carbon results to FIA-plot results either for planning, double-checking, or verification. This is especially important if FIA data are used for carbon monitoring.

The CRM is based on the assumption that component ratios calculated in Jenkins and others (2003) can be accurately adopted and applied to the predictions of sound bole volume. That is, it is assumed the merchantability standards for a tree bole in Jenkins and others (2003) are the same merchantability standards for a bole measured for FIA volume. (For instance, top height is a standard, such as height to a 4-inch top.) This method allows the user to plug in any volume and convert it to a biomass estimate. An interesting hypothesis to test is whether it would be more accurate to predict aboveground biomass and then estimate volume as a proportion of biomass. Merchantability standards of volume have continued to change, but the definition of total biomass is has always included all biomass of the tree.

The urban tree biomass scientific community also has biomass equations for their estimates, and these equations and estimates should also be taken into consideration when adopting methods for forest biomass estimates. Biomass estimates for forest land that recently converted to urban land without loss of trees should be similar to urban forest biomass estimates. Otherwise, artificial changes will be induced. One example set of biomass equations created for urban tree biomass estimates is presented in Nowak and others (2002).

Conclusions and Recommendations

The CRM produced biomass estimates that feature nationally consistent specific gravities, and biomass consistent with volumes. However, because CRM is based on volume equations which still differ by FIA unit, biomass estimates for the same species and diameter can differ by unit. If we had a consistent national volume approach, biomass based on volumes would be nationally consistent also. Additional items were identified as work that was needed to be done before biomass equations based on CRM were completed. A key assumption of this approach is that merchantable bole in Jenkins and others (2003) is equivalent in definition to the bole in the volume equations. The validity of this assumption should be further investigated. Biomass estimates in terms of tons per acre based on this approach were almost always less than the regionally based estimates and the Jenkins and others (2003) estimates. This is a curious result that may be worth investigating further.

There were additional research questions identified as a result of this preliminary analysis. Did the perceived over-prediction of biomass in the Jenkins and others (2003) biomass equations for larger trees, and lack of a deduction for damaged and standing dead trees, over-estimate total biomass? Are the small tree adjustments in CRM under-predicting biomass? Are there problems with the specific gravities used in the CRM? Would the biomass estimates be significantly different if specific gravity was based on samples from the field rather than using average compiled specific gravities?

The Jenkins and others (2003) biomass equations were developed and adopted for producing tree biomass carbon estimates because of regional differences in approaches by FIA units and database limitations. Adopting CRM immediately will hinder use of current U.S. Forest Service carbon estimates and tools based on the Jenkins and others (2003) equations, because consistency across time is critical. Because CRM is fundamentally based on volume, when volume estimates change, then biomass and carbon estimates based on the CRM will change. Since volume updates are planned in the near future in some regions, adopting CRM now means carbon estimates will change as the volume estimates are updated.

Adopting new approaches that are an improvement to existing protocols is inevitable and underway. A planned, coordinated, supported and funded national effort across FIA units and with other interested scientific experts to develop tree level volume, biomass, and carbon equations would increase the credibility and usefulness of the resulting biomass estimates, providing "high-quality, consistent, and reliable data." Ideally, for the long term, a several-year effort involving a team of scientists that allows for data mining of existing studies and data collection for validation data, sets selection criteria, works through inconsistencies, and garners support of our users will be well worth the investment. Equations for calculating tree biomass for carbon in urban forests, agroforestry systems, and perhaps subtropical and tropical forests of U.S. territories and biomass for bioenergy plantations could also be considered for inclusion in such a study.

Acknowledgments and Attributions

Pat Miles contributed the pre-publication database of specific gravity; Brad Smith contributed his idea of using a biomass expansion factor approach, and agreed to contribute the specific gravity database as well; Jim Smith developed and wrote the example and checked calculations; Mark Hansen provided the analysis for the component ratio method and figures and estimates, and substantial rewrite edits; Linda Heath conducted the literature review, developed the outline, wrote the first draft, dealt with reviewers, and takes full responsibility for the recommendations.

Literature Cited

Bechtold, William A.; Patterson, Paul L., eds. 2005. The enhanced forest inventory and analysis program - national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p.

Brown, Sandra; Gillespie, Andrew J.R.; Lugo, Ariel E. 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science. 35(4): 881-902.

Cochran, P.H.; Jennings, J.W.; Youngberg, C.T. 1984. Biomass estimators for thinned second-growth ponderosa pine trees. Res. Note PNW-RN-415. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 6 p.

Flewelling, J.W.; Raynes, L.M., 1993. Variable-shape stem-profile predictions for western hemlock. Part I. Predictions from DBH and total height. Canadian Journal of Forest Research. 23: 520–536.

Gholz H. L.; Grier C. C.; Campbell A.G.; Brown A.T. 1979. Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Research Paper 41. Corvallis, OR: Forest Research Laboratory, Oregon State University. 37 p.

Hahn, J. T.; Hansen, M. H. 1991. Cubic and board foot volume models for the Central States. Northern Journal of Applied Forestry. 8:47-57.

Hansen, Mark. 2002. Volume and biomass estimation in FIA: national consistency vs. regional accuracy. In: McRoberts, R.E.; Reams, G.A.; Van Deusen, P.C.; Moser, J.W., eds. Proceedings of the third annual forest inventory and analysis symposium; Gen. Tech. Rep. NC-230. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 109-120.

Hoover, Coeli; Rebain, Stephanie. 2008. The Kane Experimental Forest carbon inventory: Carbon reporting with FVS. In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third forest vegetation simulator conference; 2007 February 13-15; Fort Collins, CO. Proc. RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 17-22.

Heinz Center. 2002. State of the nation's ecosystems report. Cambridge, UK: Cambridge University Press. 288 p.

Heinz Center. 2005. Web only update. http://www.heinzctr.org/ecosystems/2002report/index.html (11 Dec 2008).

Heinz Center. 2008. The state of the nation's ecosystems 2008: measuring the land, waters, and living resources of the United States. Washington, DC: Island Press. 368 p.

Houghton J.T., Meira Filho L.G., Lim B., Treanton K., Mamaty I., Bonduki Y., Griggs D.J.; Callander B.A., eds. 1997. Revised 1996 intergovernmental panel on climate change guidelines for national greenhouse inventories. Paris: IPCC/OECD/IEA. (see page 5.18)

Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. 2003. National scale biomass estimators for United States tree species. Forest Science. 49(1): 12-35.

Jenkins, J.; Chojnacky, D.; Heath, L.; Birdsey, R. 2004. Comprehensive database of diameter-based biomass regressions for North American tree species. Gen. Tech. Rep. NE-319. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

Lambert, M.-C.; Ung, C.-H.; Raulier, F. 2005. Canadian national tree aboveground biomass equations. Canadian Journal of Forest Research. 35: 1996-2018. Muukkonen, P. 2007. Generalized allometric volume and biomass equations for some tree species in Europe. European Journal of Forest Research. 126: 157-166.

NCASI, Inc. 2008. COLE: Carbon OnLine Estimator, Version 2.0. Available: http://ncasi.uml.edu/COLE [11 December 2008].

Nowak, David J.; Crane, Daniel E.; Stevens, Jack C.; Ibarra, Myriam. 2002. Brooklyn's urban forest. Gen. Tech. Rep. NE-290. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 107 p.

Office of Management and Budget. 2004. Final information quality bulletin for peer review..Available: http://www.whitehouse.gov/omb/inforeg/peer2004/peer_bulletin.pdf [11 Dec 2008].

Pearson, Timothy R.H.; Brown, Sandra L.; Birdsey, Richard A. 2007. Measurement guidelines for the sequestration of forest carbon. Gen. Tech. Rep. NRS-18. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 42 p.

Penman J., Gytarsky M., Hiraishi T., Krug, T., Kruger D., Pipatti R., Buendia L., Miwa K., Ngara T., Tanabe K., Wagner F., eds. 2003. Good practice guidance for land use, land-use change and forestry. Hayama, Japan: Intergovernmental Panel on Climate Change (IPCC), IPCC/IGES.

Pillsbury, N.H.; Kirkley, M.L.1984. Equations for total, wood, and saw-log volume for thirteen California hardwoods. Res. Note PNW-RN-414. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Research Station.52 p.

Potter, Christopher; Gross, Peggy; Klooster, Steven; Fladeland, Matthew; Genovese, Vanessa. 2008. Storage of carbon in U.S. forests predicted from satellite data, ecosystem modeling, and inventory summaries. Climatic Change. 90(3): 269-282.

Raile, G.K. 1982. Estimating stump volume. Res. Pap. NC-224. St Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 4 p.

Schroeder, P.; Brown, S.; Mo, J.; Birdsey, R.; Cieszewski, C. 1997. Biomass estimation for temperate broadleaf forests of the United States using inventory data. Forest Science. 43(3): 424-434.

Somogyi, Z.; Cienciala, E.; Mäkipää, R.; Muukkonen, P.; Lohtonen, A.; Weiss, P. 2007. Indirect methods of large-scale forest biomass estimation. European Journal of Forest Research. 126: 197-207.

Smith, J.E.; Heath, L.S.; Jenkins, J.C. 2003. Forest volume-to-biomass models and estimates of mass for live and standing dead trees of U.S. forests. Gen. Tech. Rep. NE-298. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 57 p.

Smith, James E.; Heath, Linda S., Skog, K.E.; Birdsey, Richard A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Smith, J.E.; Heath, L.S.; Nichols, M.C. 2007. U.S. forest carbon calculation tool: forestland carbon stocks and net annual stock change. Gen. Tech. Rep. NRS-13. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. [CD-ROM]. Available: http://nrs.fs.fed.us/pubs/2394 [11 December 2008].

Smith, W. Brad. 1991. Assessing removals for North Central forest inventories. Res. Pap. NC-299. St Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 48 p.

Snell, J.A. Kendall; Little, S.N. 1983. Predicting crown weight and bole volume of five Western hardwoods. Gen. Tech. Rep. PNW-GTR-151. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Research Station. 42 p.

Ung, C-H; Bernier, P.; Guo, X-J. 2008. Canadian national biomass equations: new parameter estimates that include British Columbia data. Canadian Journal of Forest Research. 38: 1123-1132.

U.S. Department of Agriculture. 2008. U.S. agriculture and forestry greenhouse Gas inventory: 1990-2005. Tech. Bull. No. 1921. 161 p.

U.S. Department of Agriculture, Forest Service. 2008. FIA data and tools. http://fia.fs.fed.us/tools-data/default.asp. [19 Nov 2008].

U.S. Department of Agriculture, Forest Service. 2007. USDA Forest Service strategic plan: FY 2007-2012. FS-880. Washington, DC. 32 p. Available: http://www.fs.fed.us/publications/strategic/fs-sp-fy07-12.pdf [11 Dec 2008].

U.S. Department of Agriculture, Forest Service. 2008. The forest inventory and analysis database: database description and users manual version 3.0 for phase 2, revision 1. Washington,DC: U.S. Department of Agriculture, Forest Service, Washington Office. Available: http://www.fia.fs.fed.us/library/database-documentation/FIADB_user_manual_v3-0.pdf.

U.S. Department of Agriculture, Forest Service. 2008. Tools for carbon inventory, management, and reporting. http://www.nrs.fs.fed.us/carbon/tools/ [11 December].

U.S. Department of Energy. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. In: Section 1, Part I; forestry appendix to chapter 1, emission inventory guidelines, technical guidelines for voluntary reporting of greenhouse gas program: 2-227:Available: http://www.pi.energy.gov/enhancingGHGregistry/documents/PartIForestryAppendix.pdf (11 December 2008).

U.S. Environmental Protection Agency. 2008. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2006. EPA 430-R-08-005. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs. Available: http://epa.gov/climatechange/emissions/usinventoryreport.html [9 May 2008].

Wirth, C.; Schumacher, J.; Schulze, E-D. 2004. Generic biomass functions for Norway spruce in Central Europe—a meta-analysis approach toward prediction and uncertainty estimation. Tree Physiology. 24: 121-139.