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measurement

Estimation of Merchantable Bole Volume and Biomass above Sawlog Top in the National Forest Inventory of the United States

Grant M. Domke, Christopher M. Oswalt, Christopher W. Woodall, and Jeffery A. Turner

Emerging markets for small-diameter roundwood along with a renewed interest in forest biomass for energy have created a need for estimates of merchantable biomass above the minimum sawlog top diameter for timber species in the national forest inventory of the United States. The Forest Inventory and Analysis (FIA) program of the USDA Forest Service recently adopted the component ratio method for estimation of aboveground live tree component biomass, which incorporates regionally specific volume models by species and species group. The merchantable bole component is the biomass of sound wood from a 1.0-ft stump height to a minimum 4.0-in. top diameter. Minimum sawlog top diameters for softwoods and hardwoods in the FIA program are substantially larger than the merchantable bole top diameter, leaving additional bole biomass potentially available for utilization. This article describes a method for estimating merchantable bole biomass for the sawlog component and the component above the minimum sawlog top diameter for timber species in the FIA program.

Keywords: bioenergy, small-diameter roundwood, sawtimber, utilization, Forest Inventory and Analysis (FIA), biomass, volume

Interest in the use of small-diameter roundwood and forest-derived biomass for energy has increased dramatically in the United States over the last several decades (Boyce 1979, Skog and Rosen 1997, LeVan-Green and Livingston 2001, Galik et al. 2009, Bumgardner et al. 2013). Forest harvest residues, in particular, have been targeted as a potential carbon-friendly alternative to fossil fuels used in energy production (Repo et al. 2010, Domke et al. 2012, Goerndt et al. 2012). Aboveground tree biomass estimation procedures have historically been focused on total tree biomass with little attention given to the multitude of tree components of potential merchantability (e.g., upper bole components). Hence, forest inventories may lack resource information in regards to harvest operations that result in an abundance of residues (e.g., large-diameter sawtimber harvests).

As an initial framework for estimating tree component biomass, the Forest Inventory and Analysis (FIA) program of the US Department of Agriculture (USDA) Forest Service recently adopted the component ratio method (CRM), which incorporates regionally specific species and species group-specific volume models for estimation of aboveground live tree component biomass: top and limbs, merchantable bole, and stump (Woodall et al. 2011). The merchantable bole component is the biomass of sound wood from a 1.0-ft stump height to a minimum 4.0-in. top diameter. The sawlog component specifications vary between softwood and hardwood growing stock tree species. The minimum sawlog top diameters used in the FIA program for softwoods and hardwoods are 7.0 and 9.0 in. outside the bark (USDA Forest Service 2012), respectively. The minimum top diameter specifications for the sawlog component are substantially larger than the merchantable bole top diameter.

Currently, the FIA program does not report biomass for the sawlog component or the additional bole biomass above the minimum sawlog top diameter available for utilization and there is no documentation describing how to estimate those components. The estimation procedures documented by Woodall et al. (2011) are restricted to gross, net, and sound volume in the merchantable bole component (from a 1.0-ft stump height to a minimum 4.0-in. top diameter) for live

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Affiliations: *Grant M. Domke (gmdomke@fs.fed.us), USDA Forest Service, Forest Inventory and Analysis, Northern Research Station, St. Paul, MN. Christopher M. Oswalt (coswalt@fs.fed.us), USDA Forest Service. Christopher W. Woodall (cwoodall@fs.fed.us), USDA Forest Service. Jeffery A. Turner (jturner02@fs.fed.us), USDA Forest Service.*

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and standing dead trees because those are the estimates required to estimate total aboveground biomass and carbon in the FIA program. Those interested in estimating the biomass in the sawlog component or the additional bole volume or biomass above the minimum sawlog top diameter for timber species have relied on conversion models outside of the FIA program, which may result in a lack of additivity and alignment across other FIA component biomass estimates. This article builds on the estimation procedures described in Woodall et al. (2011) by describing a method for estimating the sound volume and biomass of the sawlog component and the component above the minimum sawlog top diameter to a minimum merchantable bole top diameter of 4.0 in. The approach is consistent with the CRM in the FIA program and allows users to estimate the additional biomass component for sawlogs with existing attributes provided in the FIA database.

Methods

The CRM for biomass estimation relies on regionally specific volume models by species and species group along with specific gravity estimates for wood and bark and estimates of the percent bark (Woodall et al. 2011). There are several estimates of tree volume currently provided in the FIA database (USDA Forest Service 2013a). Gross volume (VOLCFGRS) of live trees ≥5.0 in. dbh is defined as the total volume of wood in the central stem (1.0-ft stump height to a minimum 4.0 in. top diameter) of inventoried trees. Sound volume (VOLCFSND) is the volume of wood, not including rotten or missing cull, in the central stem, and net volume (VOLCFNET) is the volume of wood, not including rotten, missing, or form cull, in the central stem (i.e., VOLCFGRS ≥ VOLCFSND ≥ VOLCFNET). The CRM uses VOLCFSND (ft^3) to estimate merchantable bole biomass when it is available and VOLCFGRS or VOLCFNET are adjusted for the percent sound wood when it is not (Woodall et al. 2011). Estimates of gross (VOLCSGRS) and net sawlog volume (VOLCSNET) are also included in the FIA database for softwood timber species ≥9.0 in. dbh and hardwood timber species ≥11.0 in. dbh from a 1.0-ft stump height to a minimum sawlog top diameter (outside the bark) of 7.0 in. for softwoods and 9.0 in. for hardwoods. A sound volume companion to VOLCSNET and VOLCSGRS is currently not populated in the FIA database.

The top diameter of sawlogs is 3.0 in. larger than the minimum merchantable top diameter for softwoods and 5.0 in. larger than hardwoods. This difference results in a component of merchantable bole biomass above the minimum sawlog height (Figure 1), which is also not currently reported in the FIA database. The models and variables necessary for estimating sound volume and biomass in the sawlog component and merchantable bole biomass above the minimum sawlog height in the FIA program are described below.

FIA Sampling Frame

Forest data in the FIA database are collected on sample plots that are randomly defined within a hexagonal grid approximately every 6,000 acres across the 48 conterminous states of the United States. Each plot comprises a series of smaller plots (i.e., subplots) where tree- and site-level attributes, such as dbh and tree height, are measured at regular temporal intervals when the plot occurs in a forestland use (Bechtold and Patterson 2005). There are currently 120,369 plots in the annual FIA program with at least one forestland condition present.

Tree Attributes

Field protocols for measuring tree- and site-level attributes on plots with at least one forestland condition can be found in USDA Forest Service (2012). Tree diameter for timber species in the FIA program is measured at breast height (4.5 ft aboveground). Species information necessary for estimating tree volume and biomass includes species identification, wood and bark specific gravity, and bark percentage. Associated citations for each metric can be found in the REF_SPECIES table within the FIA database (USDA Forest Service 2013b) or the reference CD included in Woodall et al. (2011). Specific site- and tree-level attributes including site index, dbh, tree height, bole height, and percent volume rotten or missing can be found in the TREE and CONDITION tables in the FIA database (USDA Forest Service 2013b).

Gross Merchantable Bole Volume

Estimates of VOLCFGRS include rotten and missing parts and form cull (USDA Forest Service 2013a). Rotten and missing cull volume is estimated to the nearest 1% in the field. This estimate does not include any cull estimate above actual length so volume lost from a broken top is not included. Form cull is the percent volume that is cull due to form defect and is only needed for some locations (i.e., regional volume models) (Woodall et al. 2011). Gross volume is set to null (i.e., not available) if dbh is not available. The forms of the models to estimate VOLCFGRS are listed by FIA region in Appendixes A and B in Woodall et al. (2011), and coefficients for each model can be found in the accompanying reference CD.

Sound Merchantable Bole Volume

Estimates of VOLCFSND are calculated by deducting the rotten and missing cull volume from the VOLCFGRS estimate (Woodall et al. 2011). Note that in some instances VOLCFSND may be 0 or null and the VOLCFGRS is <0 in the FIA database (e.g., missing CULL value in the FIA database TREE table). In those cases, biomass is estimated using VOLCFGRS adjusted for the percent sound. When both VOLCFSND and VOLCFGRS are 0 or null,

Management and Policy Implications

Demand for small-diameter roundwood (<9-in. small-end diameter) and forest-derived biomass for energy has created a need for tree component volume and biomass estimates that have not traditionally been reported in the Forest Inventory and Analysis (FIA) program of the USDA Forest Service. In regions where sawtimber harvests are common, there is often additional merchantable bole biomass available for utilization above the minimum sawlog top diameters for softwoods and hardwoods. The FIA program has developed an approach for estimating sound volume and total oven-dry biomass in the merchantable bole above the minimum sawlog top diameter for growing stock timber species in the United States that is consistent with the estimation of other tree components in the FIA database. The methods described will be useful in assessments of physical availability of woody biomass for energy feedstock as well as for estimates of merchantable volume and biomass availability for forest products (e.g., pulp, lumber, and firewood).

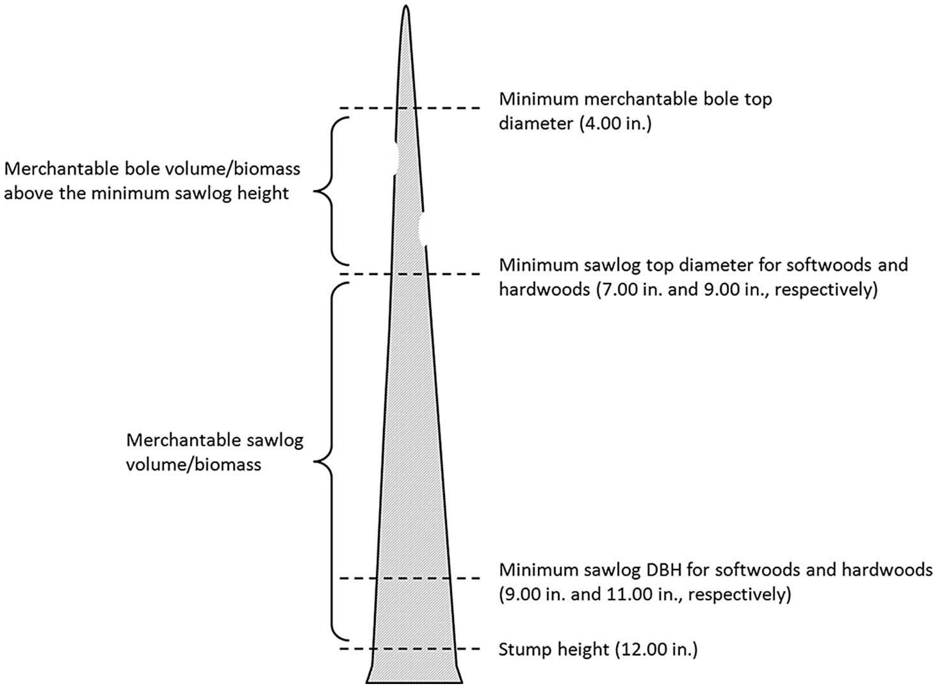

Figure 1. Individual tree components used in the FIA program to estimate merchantable bole volume/biomass above minimum sawlog top height. All growing stock timber species ≥9.0 in. dbh and hardwood timber species ≥11.0 in. dbh should have entries in the FIA database. The sawlog portion is from a 1.0-ft stump height to a minimum top diameter of 7.0 in. for softwoods and 9.0 in. for hardwoods.

biomass is estimated using VOLCFNET adjusted for the percent sound (Woodall et al. 2011). The forms of the models to estimate VOLCFSND from VOLCFGRS are listed by FIA region in Table 5 of Appendix A in Woodall et al. (2011), and the model coefficients can be found in the accompanying reference CD.

Sawlog Volume

Estimates of sawlog volume (VOLCSGRS and VOLCSNET) are calculated in a manner similar to that for VOLCFGRS and VOLCFNET in the FIA program; however, the estimates are limited to growing stock timber species that meet the minimum sawlog size for softwood and hardwood species (i.e., at least one 12-ft log or two noncontiguous merchantable 8-ft logs) (USDA Forest Service 2012) and are adjusted using taper models to the minimum sawlog top height for softwood and hardwood species. Sound volume is used in the CRM to estimate live tree merchantable bole biomass so sound sawlog volume (a new variable VOLCSSND) must be estimated from VOLCSGRS to estimate biomass in the sawlog component. The models and model coefficients used to estimate VOLCSSND from VOLCSGRS are the same as those used to estimate VOLCFSND from VOLCFGRS. In the Northeast, Rocky Mountain, Pacific Northwest (California, Oregon, and Washington), and Southern regions deductions for missing and rotten cull are estimated as

$$VOLCFSND = VOLCFGRS\left(1 - \frac{x_1}{100}\right) \quad (1)$$

where *VOLCFSND* is volume of wood excluding rotten and missing cull in the central stem from a 1.0-ft stump height to a minimum 4.0-in. top diameter, *VOLCFGRS* is volume of wood including rotten and missing cull in the central stem from a 1.0-ft stump height to a minimum 4.0 in. top diameter, and $x_1/100$ is percent volume that is rotten or missing (designated CULL in the FIA database TREE table). In the North Central region, deductions for missing and rotten cull are estimated as

$$VOLCFSND = VOLCFGRS\left(1 - \frac{b_1 b_2}{100}\right) \quad (2)$$

where b_1 is volume defect by species and tree class code and b_2 is proportion of volume (0.10−0.75) that is rotten or missing by tree class code found in the accompanying reference CD in Woodall et al. (2011). Sound volume for trees in the Central States region is estimated as

$$VOLCFSND = VOLCFGRS\left(1 - \frac{V_1 b_3}{100}\right) \quad (3)$$

where $V_1 = b_0 + b_1$ dbh if dbh is $<b_2$, b_0 and b_1 are volume defect coefficients by species and tree class code found in the accompanying reference CD in Woodall et al. (2011), b_2 is the volume defect by species and tree class code, b_3 is the proportion of volume (0.10–0.75) that is rotten or missing by tree class code found in the accompanying reference CD in Woodall et al. (2011). If $V_1 > 100$, set V_1 to 100, if $V_1 < 0$, set V_1 to 0, and if $V_1 b_3 > 98$, set $V_1 b_3$ to 100. If dbh $\geq b_2$, then $V_1 = b_0 + b_1 b_2$, if $V_1 > 100$, set V_1 to 100, if $V_1 > 0$, set V_1 to 0, and if $V_1 b_3 > 98$, set $V_1 b_3$ to 100; otherwise, $VOLCFSND = 0$. After calculations for VOLCFSND in the Northeast, Rocky Mountain, Pacific Northwest, and Southern regions, VOLCSSND can be estimated using the same model (1), only replacing VOLCFGRS with VOLCSGRS as

$$VOLCSSND = VOLCSGRS\left(1 - \frac{x_1}{100}\right) \quad (4)$$

where *VOLCSSND* is volume of wood excluding rotten and missing cull in the sawlog portion of the central stem of softwood timber species ≥9.0 in. dbh and hardwood timber species ≥11.0 in. dbh from a 1.0-ft stump height to a minimum sawlog top diameter (outside the bark) of 7.0 in. for softwoods and 9.0 in. for hardwoods, *VOLCSGRS* is volume of wood including rotten and missing cull in the sawlog portion of the central stem of softwood timber species ≥9.0 in. dbh and hardwood timber species ≥11.0 in. dbh from a 1.0-ft stump height to a minimum sawlog top diameter (outside the bark) of 7.0 in. for softwoods and 9.0 in. for hardwoods, and $x_1/100$ is percent volume that is rotten or missing (designated CULL in the FIA database TREE table). In the North Central region, VOLCSSND can be estimated using the same model (2) for VOLCFSND, only replacing VOLCFGRS with VOLCSGRS as

$$VOLCSSND = VOLCSGRS\left(1 - \frac{b_1 b_2}{100}\right) \quad (5)$$

Sound volume for trees in the Central States region, VOLCSSND, can be estimated us-

Table 1. Tree- and site-level attributes for each tree used to estimate volume and biomass in the example calculations.

Example trees	Tree class code	Cull (%)	dbh (in.)	Tree height (ft)	Site index (ft)	Basal area (ft^2)	Gross volume (ft^3)	Wood specific gravity	Bark specific gravity	Bark volume (%)
Pinus taeda	2	10	15.00	68.00	–	47.77	31.58	0.47	0.33	16.60
Pinus resinosa	2	0	15.00	91.00	72.00	183.63	31.57	0.41	0.27	16.00

ing the same model (3) for VOLCFSND, only replacing VOLCFGRS with VOLCSGRS as

$$VOLCSSND = VOLCSGRS\left(1 - \frac{V_1 b_3}{100}\right) \quad (6)$$

The component of merchantable bole volume above the minimum sawlog top height can then be estimated by subtraction as

$$VOLCSTOP = VOLCFSND - VOLCSSND \quad (7)$$

where *VOLCSTOP* is merchantable bole volume above the sawlog portion, minimum sawlog top diameter (outside the bark) of 7.0 in. for softwoods and 9.0 in. for hardwoods, to a minimum merchantable bole top diameter (outside the bark) of 4.0 in.

Sawlog Component Biomass

Biomass in the merchantable bole (DRYBIO_BOLE) of a species is estimated by multiplying the VOLCFSND (or VOLCSSND) by the weight of water to convert volume to mass and then multiplying by the specific gravity of wood and bark, separately for the species listed in the REF_SPECIES table in the FIA database (USDA Forest Service 2013b). The specific gravity of bark and wood are different. The bark component includes an additional term, bark as a proportion of wood volume, so the two components must be estimated separately and then summed. The merchantable bole wood biomass above the sawlog portion may be estimated as

$$B_w = VOLCSTOP \times SG_w \times W \quad (8)$$

where B_w is oven-dry biomass (lb) of wood above the minimum sawlog portion (minimum sawlog top diameter [outside the bark] of 7.0 in. for softwoods and 9.0 in. for hardwoods) to a minimum merchantable bole top diameter (outside the bark) of 4.0 in., SG_w is specific gravity of wood found in the REF_SPECIES table in the FIA database (USDA Forest Service 2013b), and W is weight of 1.0 ft^3 of water (62.4 lb). The bark biomass from the merchantable bole above the sawlog portion may be estimated as

$$B_b = VOLCSTOP \times \frac{BVP}{100} \times SG_b \times W \quad (9)$$

where B_b is oven-dry biomass (lb) of bark above the minimum sawlog portion (minimum sawlog top diameter [outside the bark] of 7.0 in. for softwoods and 9.0 in. for hardwoods) to a minimum merchantable bole top diameter (outside the bark) of 4.0 in., *BVP* is bark volume (expressed as a percentage of wood volume) in the central stem found in the REF_SPECIES table in the FIA database (USDA Forest Service 2013b), and SG_b is specific gravity of bark found in the REF_SPECIES table in the FIA database. Total oven-dry biomass (lb) in the sawlog component can then be estimated as

$$B_1 = B_w + B_b \quad (10)$$

Alternatively, total oven-dry biomass (lb) in the merchantable bole above the minimum sawlog top diameter to a minimum merchantable bole top diameter (outside the bark) of 4.0 in. can be estimated using DRYBIO_BOLE in the FIA database TREE table (USDA Forest Service 2013b) as

$$B_1 = DRYBIO\_BOLE - \left((VOLCSSND \times SG_w) + \left(VOLCSSND \times \frac{BVP}{100} \times SG_b\right)\right)W \quad (11)$$

where *DRYBIO_BOLE* is oven-dry biomass (lb) in the merchantable bole from a 1-ft stump to a minimum 4-in. top diameter of the central stem (see Woodall et al. 2011 for models to estimate DRYBIO_BOLE).

Examples

This section provides step-by-step calculations for estimating sound volume in the sawlog component and merchantable bole volume and biomass above the minimum sawlog top diameter to a minimum merchantable bole top diameter of 4.0 in., assuming that gross volumes have already been estimated (i.e., VOLCFGRS) (Woodall et al. 2011). The first example is for a 15.0-in. dbh loblolly pine (*Pinus taeda* L.) tree in the Southern region with a 10% cull deduction (Table 1):

Step 1. From (1): $VOLCFSND = 31.58\ ft^3\ (1 - 10/100) = 28.42\ ft^3$.

Step 2. From (4): $VOLCSSND = 30.38\ ft^3\ (1 - 10/100) = 27.34\ ft^3$.

Step 3. From (7): $VOLCSTOP = 28.42\ ft^3 - 27.34\ ft^3 = 1.08\ ft^3$.

Step 4. From (8): $B_w = 1.08\ ft^3 \times 0.47 \times 62.4$ lb = 31.74 lb.

Step 5. From (9): $B_b = 1.08\ ft^3 \times 16.6/100 \times 0.33 \times 62.4$ lb = 3.70 lb.

Step 6. From (10): B_t = 31.74 lb + 3.70 lb = 35.44 lb.

The second example is for a 15.0 in. dbh red pine (*Pinus resinosa* Ait.) tree in the North Central region (Table 1):

Step 1. From (2): $VOLCFSND = 31.57\ ft^3\ (1 - 1.3 \times 0.10/100) = 31.53\ ft^3$.

Step 2. From (3): $VOLCSSND = 29.77\ ft^3\ (1 - 1.3 \times 0.10/100) = 27.74\ ft^3$.

Step 3. From (7): $VOLCSTOP = 31.53\ ft^3 - 27.74\ ft^3 = 1.79\ ft^3$.

Step 4. From (8): $B_w = 1.79\ ft^3 \times 0.41 \times 62.4$ lb = 45.86 lb.

Step 5. From (9): $B_b = 1.79\ ft^3 \times 16.6/100 \times 0.27 \times 62.4$ lb = 4.83 lb.

Step 6. From (10): B_t = 45.86 lb + 4.83 lb = 50.69 lb.

Conclusions

Interest in the use of small-diameter roundwood and forest-derived biomass for energy has created a need for the estimation of tree biomass components not currently available in the FIA database. The FIA program has developed an approach for estimating total oven-dry biomass in the merchantable bole above the minimum sawlog top diameter for growing stock timber species that is consistent with the estimation of other tree components in the FIA database. Because this initial approach may suffice for current data needs, future research efforts (i.e., national tree volume/biomass studies) should be directed toward refined models of all tree components across the diverse forest ecosystems and tree growth habits of the United States.

Literature Cited

BECHTOLD, W.A., AND P.J. PATTERSON. 2005. *The enhanced Forest Inventory and Analysis program—National sampling design and estimation procedures.* USDA For. Serv., Rocky Mountain Research Station, Gen. Tech. Rep. SRS-80, Fort Collins, CO. 85 p.

BOYCE, S.G. 1979. *Biological and sociological basis for a rational use of forest resources for energy and organics.* USDA For. Serv., Southeastern Forest Experiment Station, CONF-7905224, Asheville, NC. 195 p.

BUMGARDNER, M., S. BOWE, AND J. WIEDENBECK. 2013. Assessing the influence of forest ownership type and location on roundwood utilization at the stump and top in a region with small-diameter markets. *Can. J. For. Res.* 43: 376–384.

DOMKE, G.M., D.R. BECKER, A.W. D'AMATO, A.R. EK, AND C.W. WOODALL. 2012. Carbon emissions associated with the procurement and utilization of forest harvest residues for energy, northern Minnesota, USA. *Biomass Bioenergy* 36:141–150.

GALIK, C.S., R. ABT, AND Y. WU. 2009. Forest biomass supply in the Southeastern United States: Implications for industrial roundwood and bioenergy production. *J. For.* 107(2): 69–77.

GOERNDT, M.E., F.X. AGUILAR, P. MILES, S. SHIFLEY, N. SONG, AND H. STELZER. 2012. Regional assessment of woody biomass physical availability as an energy feedstock for combined combustion in the US Northern region. *J. For.* 110(3):138–148.

LEVAN-GREEN, S.L., AND J. LIVINGSTON. 2001. Exploring the uses for small-diameter trees. *For. Prod. J.* 51(9):10–21.

REPO, A., M. TUOMI, AND J. LISKI. 2010. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *Global Change Biol. Bioenergy* 3(2):107–115.

SKOG, K.E., AND H.N. ROSEN. 1997. United States wood biomass for energy and chemicals: Possible changes in supply, end uses, and environmental impacts. *For. Prod. J.* 47(2):63–69.

USDA FOREST SERVICE. 2012. *Forest Inventory and Analysis National Core Field Guide: Field data collection procedures for phase 2 plots*, version 6.0. Available online at www.fia.fs.fed.us/library/field-guides-methods-proc/docs/Complete%20FG%20Document/NRS%20FG%206.0-Oct%202012-Complete%20Document-opt.pdf; last accessed May 2, 2013.

USDA FOREST SERVICE. 2013a. *FIA database description and users manual for phase 2*, version 5.1.5. Available online at www.fia.fs.fed.us/library/database-documentation/current/ver5.1.5/FIADB_user%20manual_5-1–5_p2_02_2013_FINAL.pdf; last accessed May 2, 2013.

USDA FOREST SERVICE. 2013b. *FIA data mart,* FIADB version 5.1. Available online at apps.fs-.fed.us/fiadb-downloads/datamart.html; last accessed Mar. 13, 2013.

WOODALL, C.W., L.S. HEATH, G.M. DOMKE, AND M.C. NICHOLS. 2011. *Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the US Forest Inventory, 2010.* USDA For. Serv., Gen. Tech. Rep. NRS-88, Newtown Square, PA. 30 p.