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

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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

Interests in the use of small-diameter roundwood and forest-derived biomass for energy have 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, Geornt 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
CRM uses VOLCFSND (ft³) to estimate cull, in the central stem (i.e., VOLCFGRS wood, not including rotten, missing, or form defect) volume (VOLCFNET) is the volume of wood, not including rotten or missing trees. Sound volume (VOLCFSND) is the minimum 4.0 in. top diameter) of inventory 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 (ft³) 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. 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).
biomass is estimated using VOLCFNET adjusted for the percent sound (Woodall et al. 2011). The forms of the models to estimate VOLCFGRS from VOLCSGRS and model coefficients used to estimate mass in the sawlog component. The models estimated from VOLCSGRS to estimate biomass so sound sawlog volume (a new variable VOLCSSND) must be estimated as follows:

\[
V_{\text{VOLCSSND}} = V_{\text{VOLCFGRS}} \left( 1 - \frac{x_1}{100} \right)
\]

where \(x_1\) is volume defect by species and tree class code found in the accompanying reference CD and \(V_{\text{VOLCFGRS}}\) with \(V_{\text{VOLCSGRS}}\) as substituting for \(V_{\text{VOLCFGRS}}\) in the Northeast, Rocky Mountain, Pacific Northwest (California, Oregon, and Washington), and Southern regions, VOLCSSND can be estimated using the same model (1), only replacing VOLCFGRS with VOLCSGRS as

\[
V_{\text{VOLCSSND}} = V_{\text{VOLCFGRS}} \left( 1 - \frac{x_2}{100} \right)
\]

where \(V_{\text{VOLCSSND}}\) is volume of wood excluding rotten and missing cull in the sawlog portion of the central stem of softwood timber species \(\geq 9.0\) in. dbh, and hardwood timber species \(\geq 11.0\) in. dbh from a 1.0-ft stump height to a minimum sawlog top diameter of 7.0 in. for softwoods and 9.0 in. for hardwoods.

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 VOLCFSD) must be estimated from VOLCSGRS to estimate biomass in the sawlog component. The models used to estimate volume for trees in the Central States region is estimated as

\[
V_{\text{VOLCFSD}} = V_{\text{VOLCFGRS}} \left( 1 - \frac{V_{1}}{100} \right)
\]

where \(V_{1} = b_0 + b_1 \times \text{dbh}\) 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). If \(V_{1} > 100\), set \(V_{1} = 100\), if \(V_{1} < 0\), set \(V_{1} = 0\), and if \(b_1 b_2 > 98\), set \(V_{1} = 98\) to 100. If dbh \(\geq b_2\), then \(V_{1} = V_{1} b_2, b_2 \times \text{dbh}\) if dbh \(> 98,\) set \(V_{1} = 100\), if \(V_{1} > 0\), set \(V_{1} = 0\), and if \(V_{1} b_2 > 98\), set \(V_{1} = 100\); otherwise, \(V_{\text{VOLCFSD}} = 0\). After calculations for VOLCFSD 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

\[
V_{\text{VOLCSSND}} = V_{\text{VOLCSGRS}} \left( 1 - \frac{x_3}{100} \right)
\]

where \(V_{\text{VOLCSSND}}\) is volume of wood excluding rotten and missing cull in the sawlog portion of the central stem of softwood timber species \(\geq 9.0\) in. dbh, and hardwood timber species \(\geq 11.0\) 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 \(\geq 9.0\) in. dbh, and hardwood timber species \(\geq 11.0\) 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 \(x_3/100\) 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

\[
V_{\text{VOLCFSD}} = V_{\text{VOLCFGRS}} \left( 1 - \frac{b_1 b_2}{100} \right)
\]

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).
ing the same model (3) for VOLCFGRS, only replacing VOLCFGRS with VOLCSSGRS as

\[ VOLCSSND = VOLCSSGRS \left(1 - \frac{V_t b_t}{100}\right) \]

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

\[ VOLCSTOP = VOLCSSND - VOLCSSND \]

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 VOLCSSND (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

\[ B_w = VOLCSTOP \times \frac{BVP}{100} \times SG_b \times W \]

where \( B_w \) 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 central stem (see Woodall et al. 2011 for models to estimate DRYBIO_BOLE).

Alternatively, total oven-dry biomass (lb) in the sawlog component can then be estimated as

\[ B_1 = B_w + B_b \]

### 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): \( VOLCSND = 31.58 \text{ ft}^3 \times \frac{1}{10} = 31.58 \text{ ft}^3 \times 0.10 = 3.158 \text{ ft}^3 \).

Step 2. From (4): \( VOLCSSND = 30.38 \text{ ft}^3 \times \frac{1}{10} = 30.38 \text{ ft}^3 \times 0.10 = 3.038 \text{ ft}^3 \).

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

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

Step 5. From (9): \( B_b = 1.08 \text{ ft}^3 \times 0.33 \times 62.4 \text{ lb} = 3.70 \text{ lb} \).

Step 6. From (10): \( B_1 = 31.74 \text{ lb} + 3.70 \text{ lb} = 35.44 \text{ lb} \).

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): \( VOLCSND = 31.57 \text{ ft}^3 \times (1 - 1.3 \times \frac{1}{10}) = 31.57 \text{ ft}^3 \times 0.90 = 28.413 \text{ ft}^3 \).

Step 2. From (3): \( VOLCSSND = 29.77 \text{ ft}^3 \times (1 - 1.3 \times \frac{1}{10}) = 29.77 \text{ ft}^3 \times 0.90 = 26.813 \text{ ft}^3 \).

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

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

Step 5. From (9): \( B_b = 1.79 \text{ ft}^3 \times 0.33 \times 62.4 \text{ lb} = 45.86 \text{ lb} \).

Step 6. From (10): \( B_1 = 45.86 \text{ lb} + 4.83 \text{ lb} = 50.69 \text{ lb} \).

### 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**


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