Carbon Estimates of Forest Biomass for the Clatsop State Forest

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Introduction

A great deal of interest has been generated in recent years regarding the role that forested ecosystems play in the Earth's carbon cycle and their potential to sequester and store atmospheric carbon dioxide (CO_2). This interest has come about from the knowledge that human industrial activity over the last century has resulted in higher concentrations of CO_2 and other heat trapping gases in the atmosphere. Increases in the concentration of heat trapping gases in the atmosphere have been hypothesized to result in profound changes in global climate and terrestrial ecosystems. Forests exchange CO_2 with the atmosphere through the processes of photosynthesis, respiration, and decomposition. Consequently, a number of policies and programs have emerged that recognize forest carbon sequestration in carbon accounting frameworks. For example the United States' forest carbon stocks are reported as part of the overall carbon accounting under the U.N. Framework Convention on Climate Change. The U.S. also has a voluntary greenhouse gas reporting program covered under section 1605(b) of the Energy Policy Act. Under this program business entities may report their overall emissions budgets and forest carbon sequestration with rules and guidelines consistent with the Intergovernmental Panel on Climate Change (IPCC) good practice guidance for carbon accounting (Penman and others 2003). A number of carbon emissions cap and trade systems have been developing to reduce emissions of CO2 and other greenhouse gases. Most of these systems have provisions for offsets or credits for carbon sequestration from forest management projects that meet specific criteria and verification (e.g. The Hamilton Project, Western Climate Initiative).

The increasing number of climate change agreements and action plans at scales ranging from local to international has led to a greater need for information on forest carbon stocks now and in the future. In Oregon, House Bill 2200 was passed in the 2001 session with the purpose of: 1) affirming the Board of Forestry's role as the policy body to vet and perhaps adopt standards for forest carbon offsets, 2) clearly give the State Forester authority to market carbon offsets from state forestlands as well as on behalf of the Forest Resource Trust, and 3) position the Department as an aggregator of carbon offsets on behalf of willing non-federal forest landowners.

Similarly, in House Bill 3543, passed in the 2007 legislative session, the Legislative Assembly declared that it is the state's policy to reduce greenhouse gas emissions in Oregon by stopping the growth of Oregon's greenhouse gas emissions by 2010, by 2020 achieve greenhouse gas levels that are 10 percent below 1990 levels, and by 2050 achieve greenhouse gas levels that are at least 75 percent below 1990 levels. The Assembly recognized that Oregon forests play a significant role in sequestering atmospheric carbon, and losing this potential to sequester carbon will have a negative effect on our ability to reduce the concentration of atmospheric CO_2. Section 12(1) (i) charged the Oregon Global Warming Commission to track and evaluate the carbon sequestration potential of Oregon's forests, explore alternative methods of forest management that might increase carbon sequestration and reduce the loss of sequestration from wildfire, changes in mortality, changes in the distribution of trees and other plants, and the extent to which carbon is stored in tree-based building materials.

Not only is estimating the biomass of standing forests a fundamental component of managing forests for carbon sequestration and reduced risk of fire (Jenkins et al. 2003) but reliable estimates of tree biomass and leaf surface area are also essential for studying primary production, nutrient cycling, hydrology, and wildlife management (Gholz et al. 1979). Therefore, it is important that forest managers utilize information tools that are available to consistently estimate the biomass of the forest resources under their stewardship. For these reasons a forest carbon-stock analysis was initiated to begin the process of estimating and accounting for carbon storage and flux on state-owned forestland. The following report describes the methods, results, and issues encountered with the first phase of the analysis limited to estimating current carbon in live trees for the Clatsop State Forest within ODF's Astoria forest protection-management district. The two studies referenced above contain compilations of equations that use plant dimensions such as diameter at breast height (dbh) to compute dry weight biomass of the total tree and were used for calculations in the following analysis.

Methods

Data Source

To produce estimates of *current* carbon in live trees for all state-owned forest land in Oregon will require the integration of results from multiple inventories because separate databases were created for inventories from each district of state-owned forest land (Figure 1). The State Forests Stand Level Inventory (SLI) is the forest inventory system developed by Oregon Department of Forestry in 2001. It is employed on state-owned forest lands to provide current or recent information for a variety of vegetation and stand-level forest mensuration attributes and where they occur on the landscape. SLI is used for information-based decision making, focusing on facilitation and assessment of operational forest management activities. Information on vegetation elements including live and dead trees, non-tree vegetation (herbs-shrubs-grasses), and down woody material is gathered via field sampling techniques within stratified forest stands.

The Sli inventory for the Clatsop State Forest in the Astoria District was used for this initial effort at estimating the amount of carbon in live trees on state-owned forest land. The Astoria database contained 1518 stands each represented by a polygon in a GIS layer. According to entries in the database, tree and other attributes from 795 of these stands were measured and recorded between 1999 and 2007 with a large difference in the proportion of stands measured in each of those years (Figure 2). There were 152 unmeasured stands assigned a matching impute stand ID. Visual inspection of 2005 NAIP imagery showed that these stands were either clearcut, in the early stages of regenerating, or consisted of some proportion of an average stocking level at that instance in time. The average biomass per acre was assigned to the stands with average stocking, regenerating stands were assigned a value of 0.25 times the average biomass density of measured stands, and stands that showed clearcut (or imputed with a 9999 label) were assigned zero stocking. The remaining 543 unmeasured stands contained 32 that were assigned a stand ID that was not within the set of measured stands. These 32 stands were assigned the average biomass per acre for hardwood and softwoods. The remaining 511 unmeasured stands were assigned the hardwood and softwood biomass per acre values corresponding to their imputed stand assignment. The total number of unmeasured stands that received some form of imputation assignment was n = 613.

Equations

Biomass estimates were made for live aboveground parts of trees (bole, bark, branches, and foliage) and for coarse roots of trees using equations from Jenkins et al. (2004) and Gholz et al. (1979). Live tree biomass was expanded to a per-acre basis using the Sli expansion factors for individual trees. These values were summed across the plots in a stand to calculate biomass density for each measured stand. The biomass to Carbon conversion factor most commonly used consists of dividing biomass estimates by two. The Jenkins (2004) equations are species-specific and are used to calculate biomass as a function of diameter at breast height (dbh) measured on each tree of the inventory. The response profiles of biomass accumulation as a function of dbh are listed in the appendix. Fried (2008) used local volume equations utilized by PNW-Forest Inventory and Analysis (FIA) coupled with species-specific parameters for specific gravity. The regional volume equations are a function of both dbh and height measurements which are taken on each tree in the FIA protocols. The Sli inventory recorded heights on only a subset of trees so therefore, the equations based on dbh only were used. The use of the volume equations perhaps better reflects true carbon stocks but the Jenkins equations are routinely used for state-level and other analyses, in part because they are embedded in accounting systems such as the Carbon Calculation Tool reported in Smith et al.(2007) (Fried 2008).

The calculations of biomass for each tree, plot and stand were made using a programming routine that interfaces with the inventory database and the Forest Vegetation Simulator (FVS) (Dixon 2002). The routine creates tree list files and stand information files needed by FVS from information contained in separate tables of the database. FVS produces future projections of tree growth and mortality and reports the projections for discrete intervals of time for each stand. The system can be used to simulate various management scenarios to estimate the growth and yield of forested systems. FVS projections were made for each stand in the Astoria database for 100 years into the future with output at 10-year intervals. The analysis for this report is based exclusively on the first projection cycle which consists of calculations of biomass on the dbh measurements in the database. The FVS projection system requires keywords for calibrating tree growth and mortality equations based on monitoring data or other information. The system was developed for subsequent phases of carbon analyses that will include calibrating FVS and then implementing various management simulations to test ideas about optimizing carbon sequestration and fire management through time.

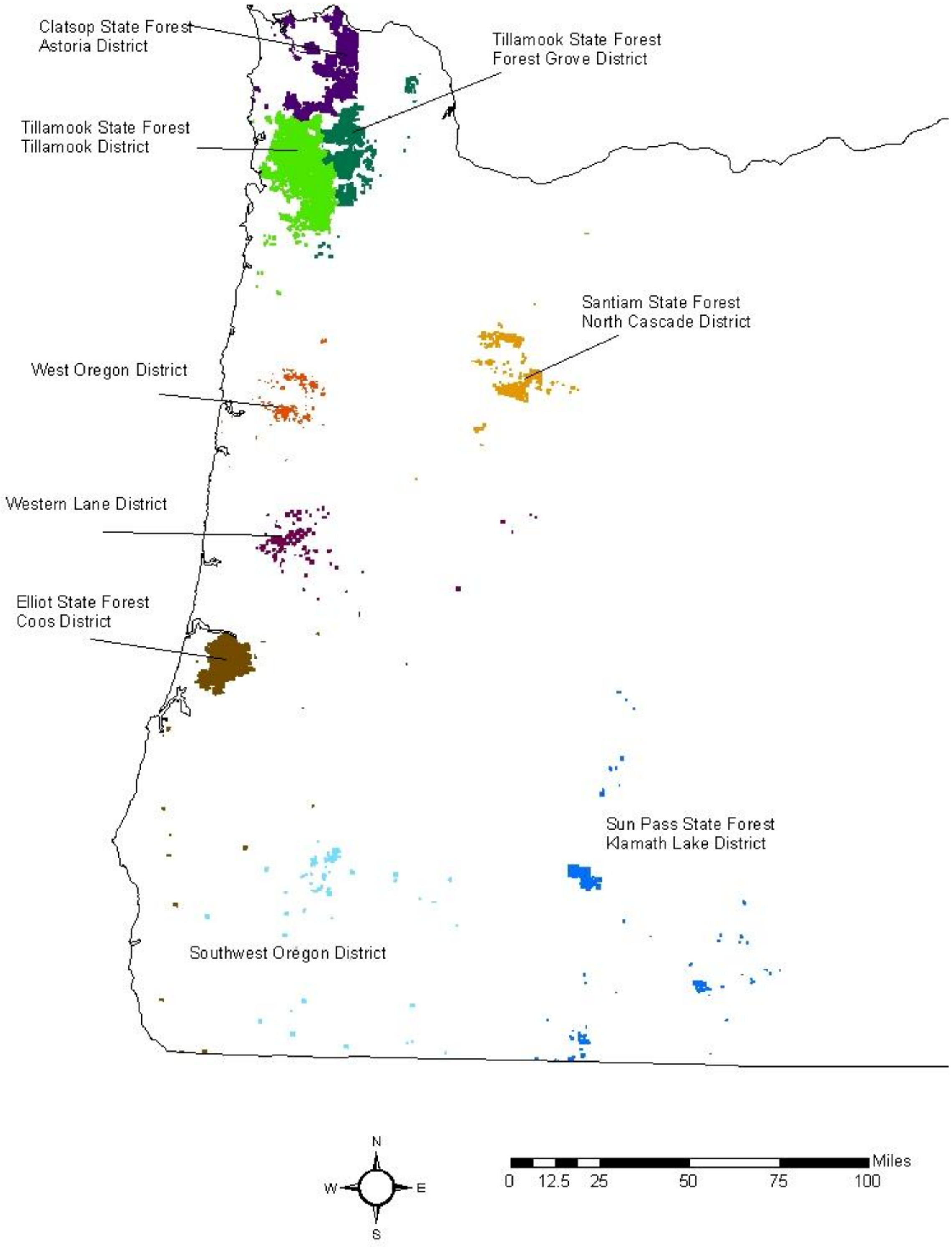

Figure 1. Map of forestland owned by the state of Oregon and managed by the Oregon Department of Forestry.

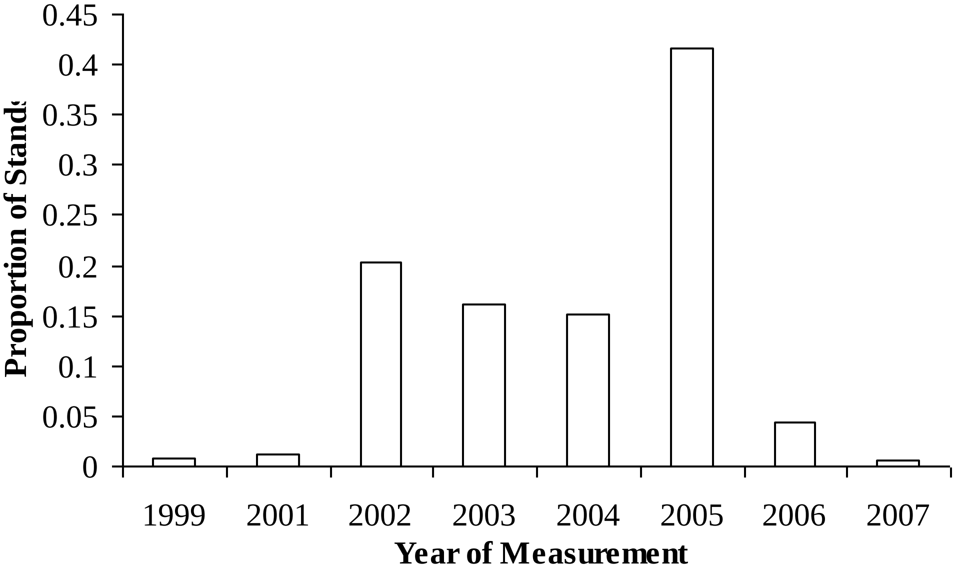

Figure 2. Proportion of stands measured each year. Data represent values from the "MSMT YR" column in the Astoria Sli database.

Results

The average biomass per unit area with hardwoods and softwoods combined calculated from the set of measured stands was 133.40 Mg /acre. The average hardwood biomass was 22.75 Mg/acre (±2.05) and the average softwood biomass was 110.65 Mg/acre (± 5.22). The average total stand biomass, hardwoods and softwoods combined, calculated from measured stands, was 17.96 Gg (± 1.89). The estimated total amount of Carbon in live trees and roots in all measured stands combined was 7.14 Tg and total carbon in unmeasured stands was calculated to be 2.44 Tg producing a total carbon estimate for the Clatsop state forest of approximately 9.58 Tg (10.56 million tons) of Carbon in live trees.

Table 1. Biomass and Carbon density estimates with 95% confidence intervals for the set of measured stands. The mass of Carbon in live trees was treated as one-half of the biomass.

-------------------------------------*Average Biomass, Mg/Acre*	---	
Hardwood	Softwood	Combined
22.75 (± 2.05)	110.65 (± 5.21)	133.40 (± 5.43)
-------------------------------------*Average Carbon, Mg/Acre*	---	
		Hardwoods + Softwoods
11.38 (± 1.03)	55.325 (± 2.61)	66.70 (±2.72)

The estimate for the average Carbon density per unit area (66.7 Mg C/acre) was slightly higher than the largest values for Carbon density in California forests estimated by Fried (2008) using the Jenkins equations. Carbon density of reserved public timberland in California was estimated to be nearly 60.0 Mg C/acre and the lowest Carbon densities occurred on unreserved public timberland at 7.54 Mg C/acre. Fried (2008) noted that the Jenkins equations produced Carbon density estimates that were generally (but not always) higher (sometimes substantially) than estimates produced using the PNW volume equations in combination with specific gravity of tree species. Hudiberg et al. (2007) estimated the live biomass density in forests of the Coast Range to average from 10.9 kg C/m^2 for young forests up to a maximum of 33.4 kg C/m^2. Expressing the average Carbon density estimated for the Clatsop State in these same units (16.48 kg/m^2) places the average age of this state owned forestland between the young and mature (22.7 kg C/m^2) classes reported in Hudiberg et al. (2007).

From inventory data collected during 2001-2005 FIA estimated Carbon density in Oregon's forests to be approximately 40 Mg C/acre (Figure 37 in Donnegan et al. 2008) with highest densities in the western hemlock/Sitka spruce (~59 Mg C/acre) forest type group followed by Douglas fir (~ 44 Mg C/acre). These estimates are lower than those for the Carbon density in the Astoria District's Clatsop state Forest and appear to lend support for Fried's results that the Jenkins equations yield higher estimates than the volume equations used by PNW-FIA. However, the FIA five-year report shows that the average volume/acre on state-owned forestland is approximately 1500 cubic feet/acre higher than Forest Service forest land that has the next highest mean volume densities. In old growth forests of the PNW average Carbon densities of live-trees have been estimated to range from 202 Mg C/acre (500 Mg C ha^{-1}) for total trees (Janisch and Harmon 2002), approximately 174 Mg C/acre (430 Mg C ha^{-1}) (Harmon et al. 1990), and approximately 226 Mg C/acre (560 Mg C ha^{-1}) (Smithwick et al. 2002).

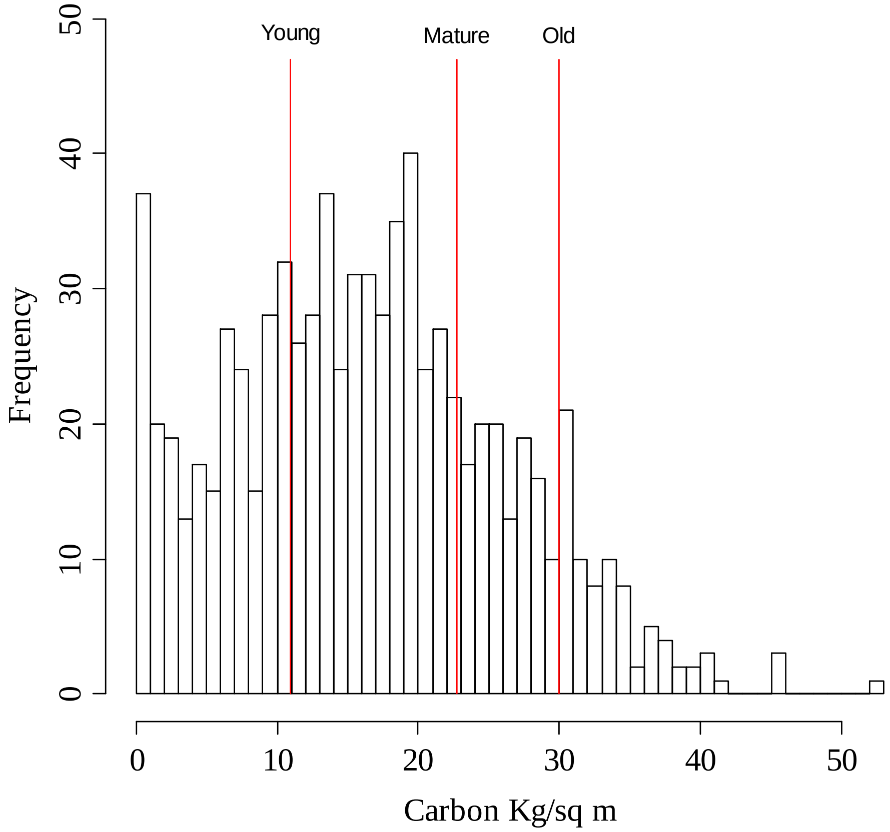

Figure 3. Frequency histogram for the Carbon density estimates, in kg/m^2, of all measured stands in the Astoria sli database. The superimposed lines for young (< 80 yr), mature (80-200 yr), and old (>200 yr) represent the mean carbon density for these three age groups in Coast Range forests as estimated by Hudiberg et al. (2007).

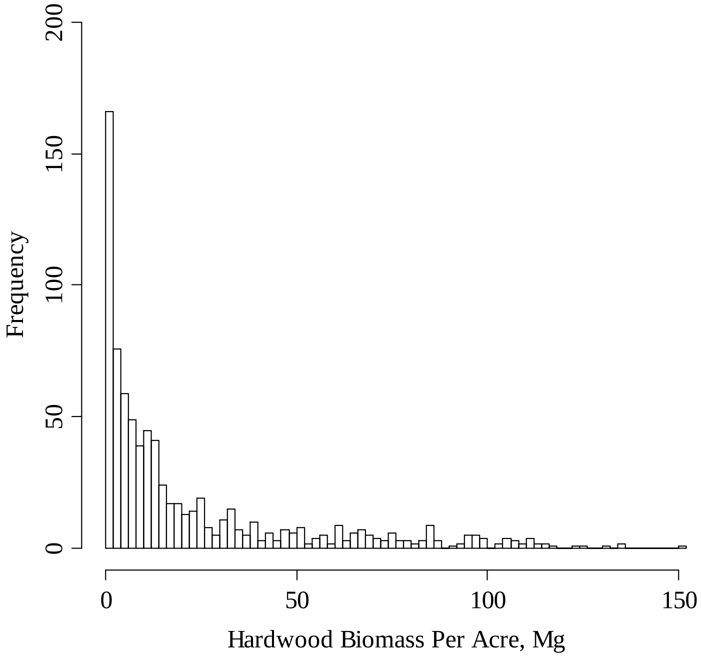

Figure 4. Frequency histogram for the estimated megagrams of biomass per acre (above and below ground) for hardwood species based on stands measured in the Astoria Sli inventory.

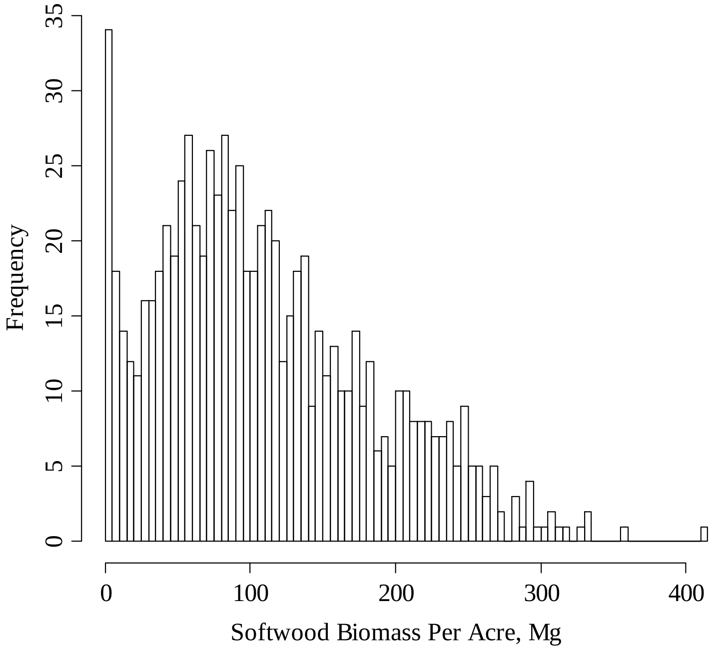

Figure 5. Frequency histogram for the estimated megagrams of biomass per acre (above and below ground) for softwood species based on stands measured in the Astoria Sli inventory.

Discussion

Forestry may be the only sector of Oregon's economy that has a negative value for the net amount of emissions. As a market in carbon credits develops, the amount of carbon stored in young, actively growing forests may be used to help offset carbon released from urban and industrial components of the economy. However, estimating the amount of carbon sequestered in the live trees of forested ecosystems through time requires multi-temporal comparisons of biomass inventories and removals from mortality or transfer to building materials. Fried (2008) stated that "for estimating the change in [forest] carbon stocks as a proxy for carbon flux, it is essential to perform calculations on comparable inventories, and ideally, on a remeasurement inventory in which the same plots and trees are measured with essentially the same protocols several years apart." The standardization of sampling designs, field protocols, data organization and storage, and analyses through time must become a common goal among forest resource management agencies. Until the ideal forest inventory and monitoring system is implemented across all forestland and standardized through time natural resource agencies must rely on existing forest inventories that were not designed for precise accounting of carbon storage and flux.

Although the Carbon density for the set of stands that comprise the Clatsop state forest, based on the most recent inventory, were calculated to be slightly higher those for the highest carbon densities found in California's reserved forests they are still roughly 100 Mg/acre lower than estimates of carbon density in old growth forests of the Pacific Northwest. The estimate of total carbon and carbon density produced from this analysis should be considered a rough approximation since the methodology used was based on equations that do not use height measurements in combination with dbh. Without accurate height measurements on all (or a large number of) measured trees the use of volume equations in combination with the specific gravity of wood density for each species would still produce rough approximations. The Jenkins equations used for this analysis were relatively easy to implement although equations for roots and other components for many species were incomplete. The appendix describes how the equations for each species were utilized within the range of dbh values they were developed from and the substitutions that were made to compensate when dbh measurements exceeded the dbh range. Furthermore, the use of volume equations to estimate biomass would also have to utilize component ratios that are rough approximations to estimate foliage, branches, bark, and roots.

Another issue worth considering is the accuracy of the imputation of stand attributes of measured stands to the set of unmeasured stands in the database. Although guidelines have recently been developed for the imputation procedure they have yet to be implemented for every forest inventory database within the Sli system. The imputation procedure for the Astoria database was carried out using experience and knowledge of local forest managers. The implication of these facts is that implementation of the new procedure might produce results different than those reported from the analysis described above.

There are multiple pools of carbon in forested ecosystems. The estimates for biomass and carbon reported in this study apply only to the live-tree component of the Sli inventory. Future work might involve utilizing the dead wood component to estimate the carbon storage in this pool for state forest land. The FIA inventory shows that there is almost three times as much live-tree biomass as dead-wood biomass. Based on this approximation alone the Clatsop State Forest might contain ~3.2 Tg of Carbon in the dead wood component.

Unit Conversions

1 lbs = 453.59 grams
1 Gg = $1X10^{9}$ grams
1 Tg = $1X10^{12}$ grams
1 ha = 2.471 acres
1 acre = 4046.856 m^{2}

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APPENDIX

Biomass equations

The analysis that follows examines the use and behavior of these equations for estimating the biomass of individual species that occur in the Forest Inventory and Analysis (FIA) Western Oregon database for private forest land. Biometric information for forested ecosystems is typically estimated from aggregated plot-level statistics computed from individual measurements of trees (e.g. height, dbh, species, etc..) (Jenkins et al. 2003). Basically, a researcher samples many stems spanning the diameter and height range of interest then uses a regression model to estimate the allometric relationship that exists between tree dimension and tree component weights. Tree components refer to foliage, stem wood, bark wood, roots, or branches. Thus, carbon, which is roughly one-half the value of biomass, in live trees is directly tied to inventory measurements and is most affected by human activities and natural disturbances.

Acronym convention

The equations for tree biomass from Gholz et al. (1979) Table A.1 and variables within the visual basic code follow the acronym convention of Table 3 in GTR NE-319 (Jenkins et al. 2004). It is important to note that the variable acronym conventions are not the same between Gholz et al. and GTR-319. For example BST in Gholz et al. represents stem wood biomass and BBK is bark only. The GTR NE-319 distinguishes wood biomass as BSW and BSB is bark only. BSB in Gholz et al. represents bark and wood biomass. BLB in Gholz is branch biomass but is BBL in GTR-319. So there are several differences between the two sets of equations which could lead to confusion. Therefore, the decision was made to maintain consistency with GTR-319 in acronym usage within the computer coding of the equations. The primary reason for the GTR-319 acronyms is because the database is much larger than Gholz et al. (in terms of the number of species and equations for each), integrates some of the latter's equations, and therefore provides more information and possibilities. The Gholz et al. equations were used for major tree species within its domain because of the consistency of minimum and maximum diameter range used for the various tree parts BSW, BST, BBL etc. For diameters greater than 2.5 cm and less than or equal to the minimum diameter of the main equation the total above ground biomass for hardwood and softwood species groups was estimated with the equations in Table 4 of Jenkins et al. (2003). GTR-319 equations were used elsewhere.

Cautions

Gholz et al. drew attention to the fact that the equations should be used carefully because misuse of equation forms may cause large errors. One caution is negative intercepts that can occur could lead to negative values for small plants…accumulating over a whole watershed resulting in gross underestimates. Estimates made from values near the lower and upper ranges of the independent variable, dbh, may not always provide reasonable numbers. Before extrapolating beyond the data, each equation should be evaluated with examples.

Species and response profiles from biomass equations

The information that follows consists of a description of how biomass equations were implemented for each species. Tree diameters from database that was used to test the correct coding came from the 1997 interval of the FIA database for Western Oregon.

Douglas fir, *Pseudotsuga menziesii*

There are 6 equations for AGBM from Gholz et al. that are good through a dbh range from 1.8 to 162 cm. The results of these are summed to estimate AGBM. A straight line from zero is used for dbh's less than 1.8 (Figure 1). The discontinuity between curves at a dbh of 162 might be remedied by creating a second order polynomial between the two sets of estimates. There are only 6 tree records in the FIA database for private forests with dbh's above 162 cm. It is likely that the public forest lands database will contain a greater number of tree records above 162. Regardless the curves should have the same discontinuity at that cutoff.

There is also a root equation among the Gholz et al. set. The straight line was used for roots attached to a tree with dbh less than 1.8 (Figure 2). Although the equation is presented as valid up to a dbh of 162 cm it was applied to trees with dbh above this value and therefore the estimates for these larger diameter trees should be regarded with caution.

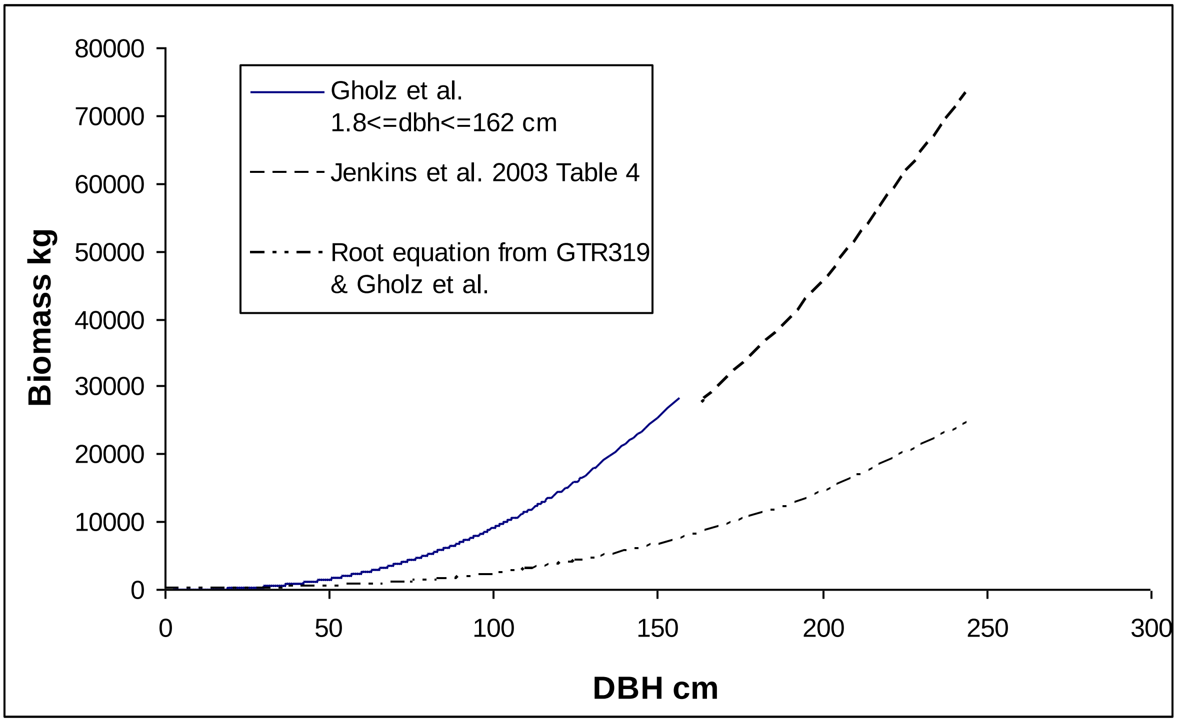

Figure 6. Aboveground and root biomass estimates for Douglas fir. Lines represent estimates calculated for each PSME tree in the FIA western Oregon database on private forest land. The line for dbh's greater than 162 cm represents six records whereas the line for the 1.8 to 162 cm dbh range represents 9588 records.

Western hemlock, *Tsuga heterophylla*

Six equations from Gholz et al. through a dbh range of 15.3 to 78 were used to estimate AGBM. The Jenkins et al. (2003), Table 4 equation for True fir/hemlock was used for dbh's above 78 cm, between 2.5 and 15.3 cm, and a straight line was used from zero to 2.5 cm dbh (Figure 2).

The root equation for eastern hemlock (GTR319, Table 3) was initially used for calculating root biomass because there isn't an equation for western hemlock roots. The estimates, however, were, on average, 4.8 times larger than the above-ground biomass. Therefore, the alternative was to apply the root equation for Douglas fir for the full distribution of dbh's in the database. The upper limit of the Douglas fir root equation is 162 cm and the largest diameter western hemlock in the database was 132 cm.

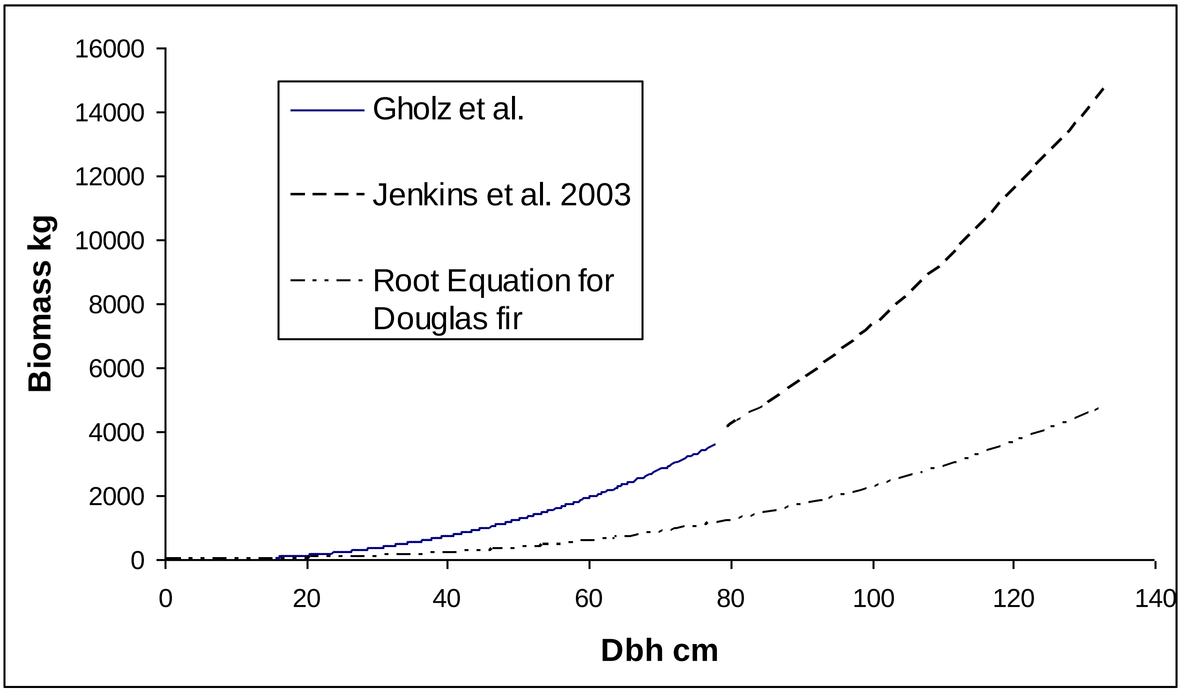

Figure 7. Above ground biomass estimates for Western Hemlock produced by two equations with a cutoff dbh of 78 cm. The curve for root biomass was produced with the root equation for Douglas fir.

Red alder, *alnus rubra*

A set of five equations for red alder from GTR 319, Table 3 were used to estimate above-ground biomass. They include BSW, BSB, BBL, BBD, BFT for a dbh range between 9.1 and 39.6 cm. For dbh's below 9.1 and above 39.6 the hardwood equation for Aspen/alder/cottonwood/willow from Jenkins et al. (2003) Table 4 was used (Figure 3).

Both the root equation for "general hardwoods" from GTR 319 (Table 3), and the root component ratio equation (Table 6) were used for estimating root biomass. The general hardwood equation is intended for a dbh range of 2.5 to 60 cm, but was applied to all trees in the database (Figure 3). The root component equation produces estimates that are much smaller than what the general hardwood equation does. Until focused research on the true relationship of root biomass to above ground biomass or a root equation as a function of dbh is developed the curves in Figure 3 are the two alternatives that are currently available. The component ratio equation might be the preferred alternative under a policy of to err on the side of caution when necessary.

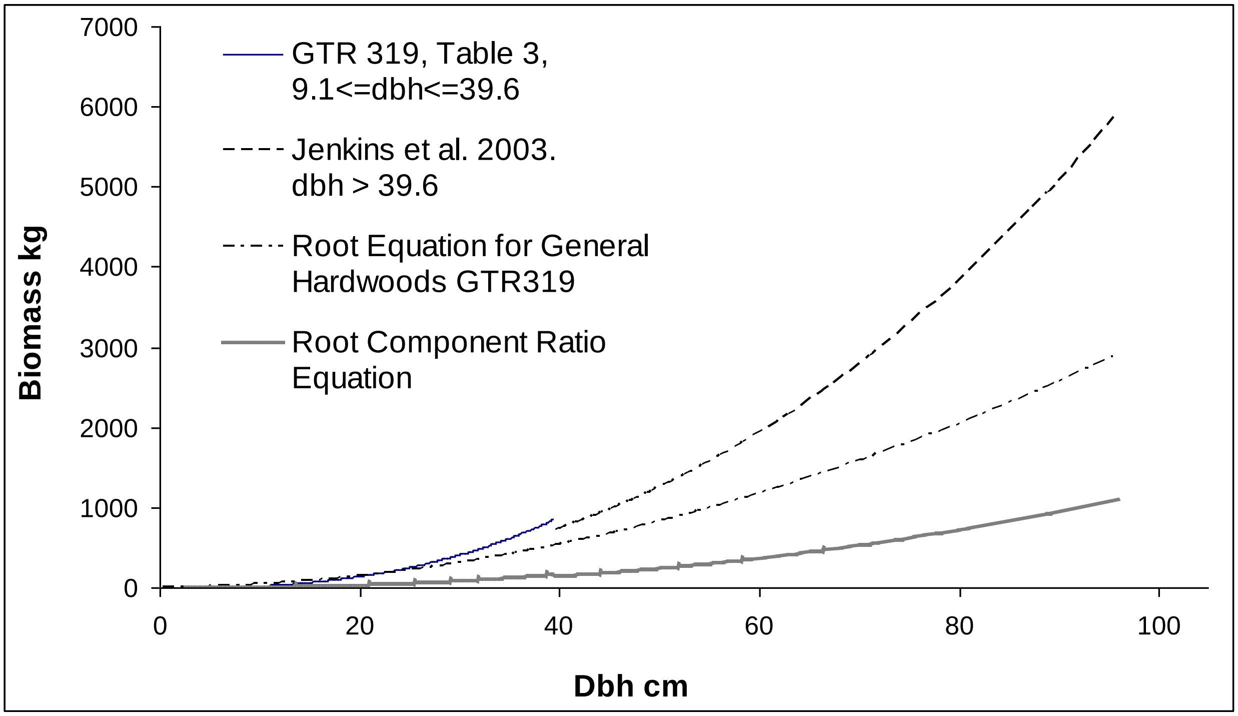

Figure 8. Above-ground and root biomass estimates for red alder. The same equations were applied to pacific madrone.

Bigleaf maple, *Acer macrophyllum*

There are 5 equations for BM tree parts, and dead bark (BDB). The diameter ranges from 7.6 cm to 35.3 cm. For dbh less than 7.6 the hard maple/oak/hickory/beech equation from Jenkins et al. (2003) was used. For trees with dbh less than 2.5 the slope of the line from zero to the estimate at 2.5 was used.

The root equation for sugar maple, an eastern distributed species, was used to estimate root biomass because there isn't one for bigleaf maple or red maple, for that matter, in the either Gholz et al or GTR 319. However, the root estimates with the sugar maple equation were very low relative to the above ground biomass (Figure 4). Therefore, the estimates for root biomass using the equation for general hardwoods was used as a reference for comparison in Figure 4. Jenkins et al. 2003 also provide parameters for estimating the ratio of aboveground biomass to other tree components (e.g. foliage, coarse roots, stem bark, stem wood). Results for sugar maple and the component equation are nearly identical but much lower than what the equation for general hardwoods produced. It appears that the estimate for root biomass could possible be too high with the general hardwood equations even though the R^2 reported in GTR319 is 0.93. On the other hand the equation for ratio of root component to above ground biomass and the equation for sugar maple might be underestimates. The component ratio equation was based on 121 data points and produced a very low R^2 of 0.029. the sugar maple equation is reported to have an R^2 of 0.95. However, the close agreement with the curve produced with the equation for sugar maple lends support for using the latter equation. Until further research produces an actual quantitative relationship conclusions from these results should take this uncertainty into account.

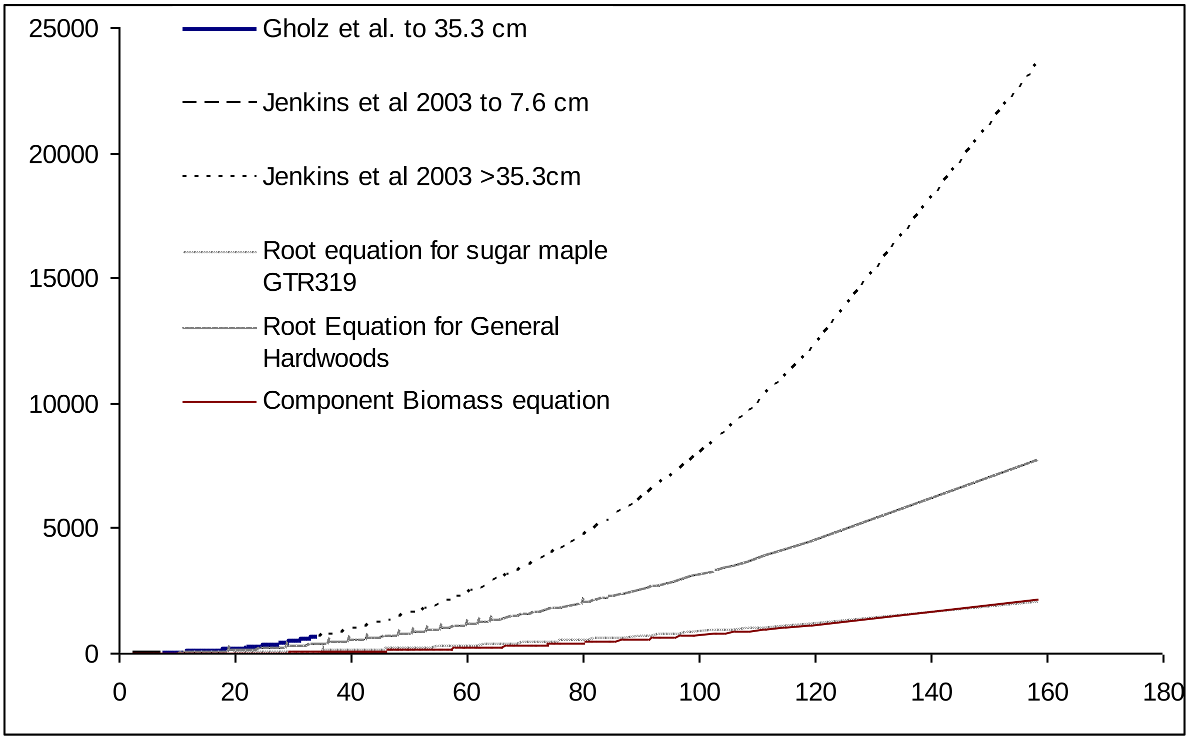

Figure 9. Above ground and root biomass response curves for big leaf maple. Three alternatives for estimating root biomass are shown.

Golden Chinkapi*n, Castanopsis chrysophylla*

There are six tree part equations for above ground biomass (AGBM) for a dbh range of 5.8 to 36.0 in Gholz et al. For dbh's between 2.5 and 5.8 cm and above 36 cm the soft maple/birch equation of Jenkins et al (2003) was used. The difference between the two equations is manifested in a small disjunct where the two curves meet at 36 cm dbh (Figure 5). Table 4 of GTR-319 contains the specific gravity of 317 tree species. The wood specific gravity (WSG) of golden chinkapin is empty. There is an entry for just chinkapin of .42. Four species of maple have a WSG of 0.44 which is closer than either hard maple/oak/hickory/beech or the aspen/alder/cottonwoods. Therefore, the soft/maple birch equation was used.

There is no biomass equation for golden chinkapin, therefore, two alternatives were explored. Figure 5 shows the biomass curve that resulted from applying the ratio component equation from Jenkins et al. (2003) and the root equation for sugar maple as a possible substitute. The estimates for the sugar maple equation begin to differ at about 60 cm dbh. Above 60 cm dbh the sugar maple estimates are lower than using the component equation. It is uncertain to how much bias there is in using either equation or another alternative. Therefore, the results should take this uncertainty into account when making conclusions.

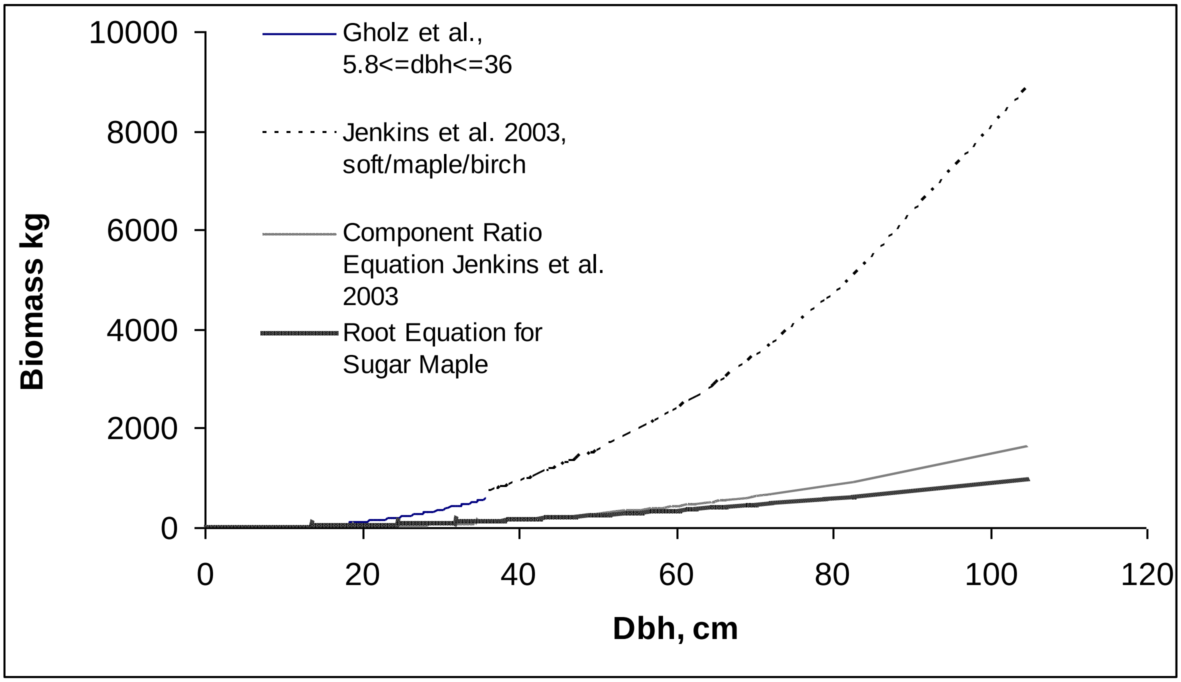

Figure 10. Above ground and root biomass responsive curves for golden chinkapin. Two alternatives are shown for estimating root biomass.

White oak, *Quercus garryana*

Four equations, BSW, BSB, BBT, and BFT from GTR319 through a dbh range of 7 to 63 cm were used for AGBM. The Jenkins et al. equation, Table 4 was used for dbh's from 2.5 to 7 and above 63 cm. The component equation for coarse roots from Jenkins et al. (2003) was used to estimate root biomass. The biomass curve produced from the root equation for general hardwoods from Table 3 of GTR319 are displayed for comparative purpose. Which equation is more accurate reflection of the actual relationship is uncertain.

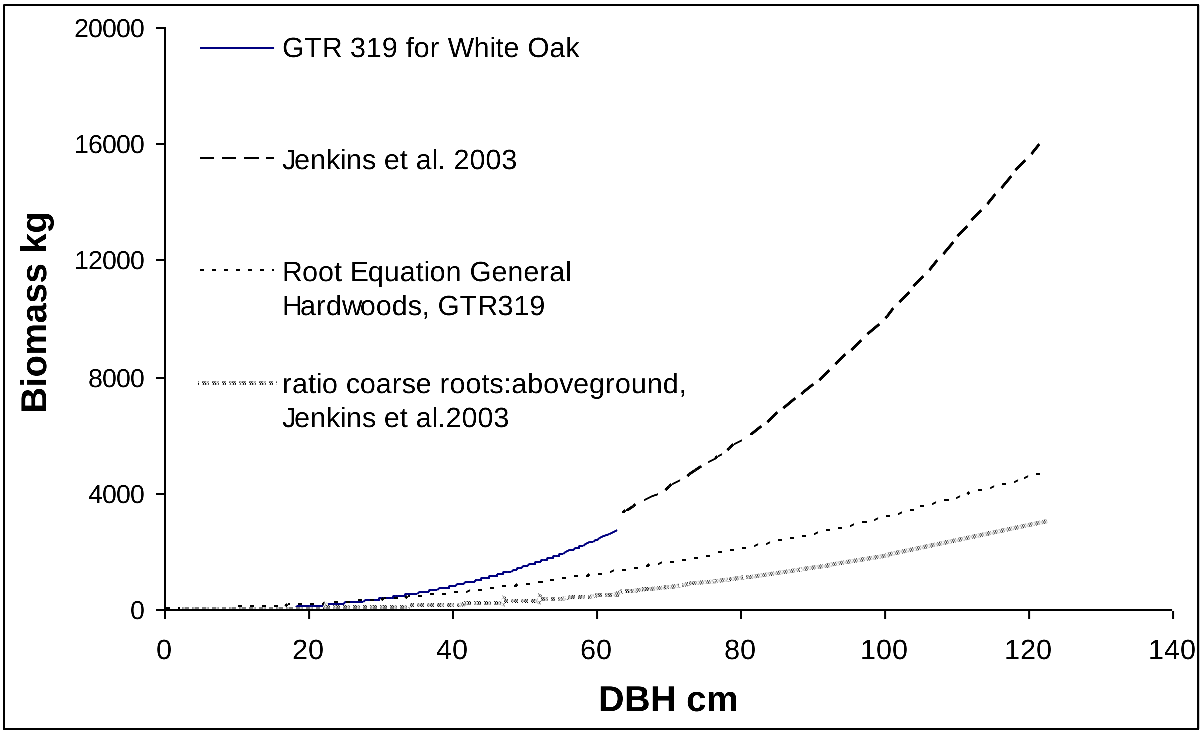

Figure 11. Responsive curves for above ground and root biomass of white oak. Two alternatives for root biomass are shown.

Western red cedar/Alaska cedar/incense cedar

There are only 3 equations for Alaska cedar in GTR319 for stem wood and bark. There are 4 equations, the same for both species, in Gholz et al. for the wood, bark, branches and foliage. Therefore, the Gholz et al. equations were used for Alaska cedar (YC), Western redcedar (WC) and incense cedar (IC) for the dbh range of 15.5 to 60.2 cm. The equation for Cedar/larch from Jenkins et al. (2003) was used for dbh's from 2.5 to 15.5 cm and dbh's above 60.2 cm.

There is a clear disjunct between the aboveground biomass curves at 60.2 cm with the Jenkins et al. (2003) estimates lower than the Gholz estimates.

The root equation for western redcedar from GTR319, Table 3 was used for a dbh range of 12 and higher. The straight line from zero to the estimate at 12 cm was used for dbh's < than 12 cm. The response curve shows the biomass of roots is less than above ground biomass, which should be expected, but the distance between the two is not as great as the distance between the curve produced by the component ratio from Table 6 of Jenkins et al. (2003).

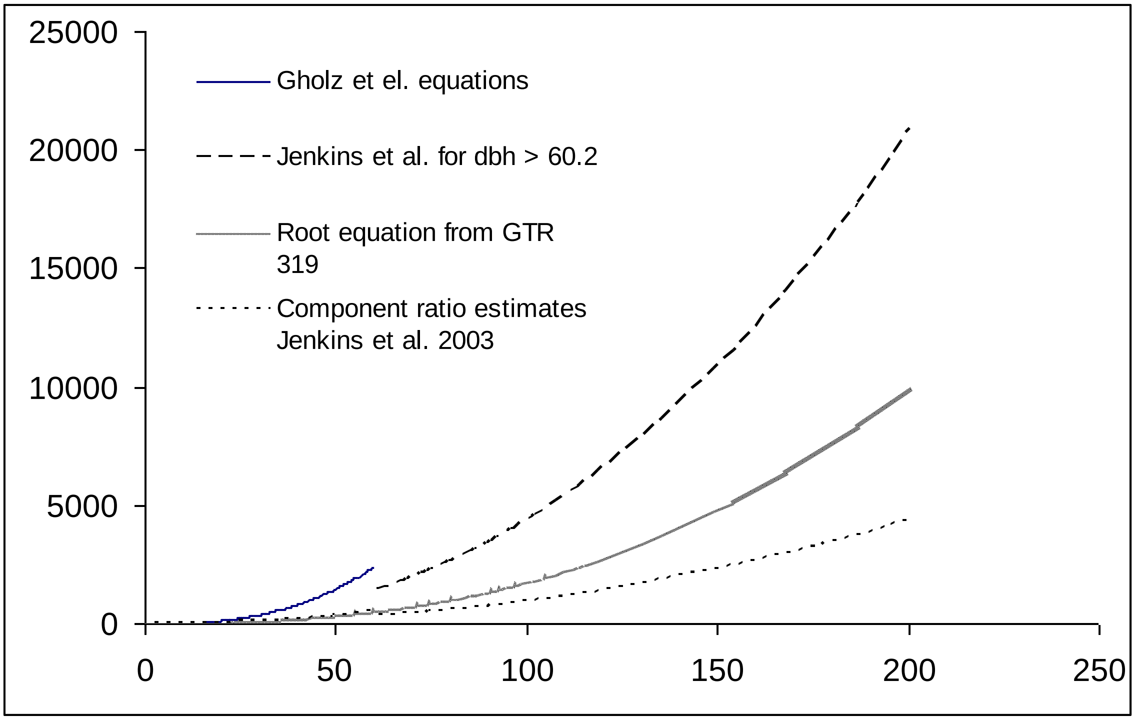

Figure 12. Above ground and root biomass response curves for western redcedar, Alaska ceder, and incense cedar.

Sitka Spruce

The GTR319 Table 3 had equations for BST, BBT,BFT through a dbh range of 15 to 55 cm. The Jenkins et al. (2003) equation for spruce was used for dbh's above 2.5 cm. The straight line from zero to 2.5 cm for dbh's less than 2.5 cm.

The root equation for spruce in general from Table 3 of GTR319 would be nice to use for estimating root biomass for sitka spruce but the equation is for stumps and roots. The curve produced had estimates that were higher than above ground biomass, and therefore, was not used. The root equation for Norway spruce is valid within a dbh range of 10 to 30 cm and was written into the code. The component ratio equation from Jenkins et al. (2003) was applied for dbh's below 10 and above 30. There is a small jump (~ 20 cm) in estimates that occurs at the 30 cm dbh point where the two equations meet.

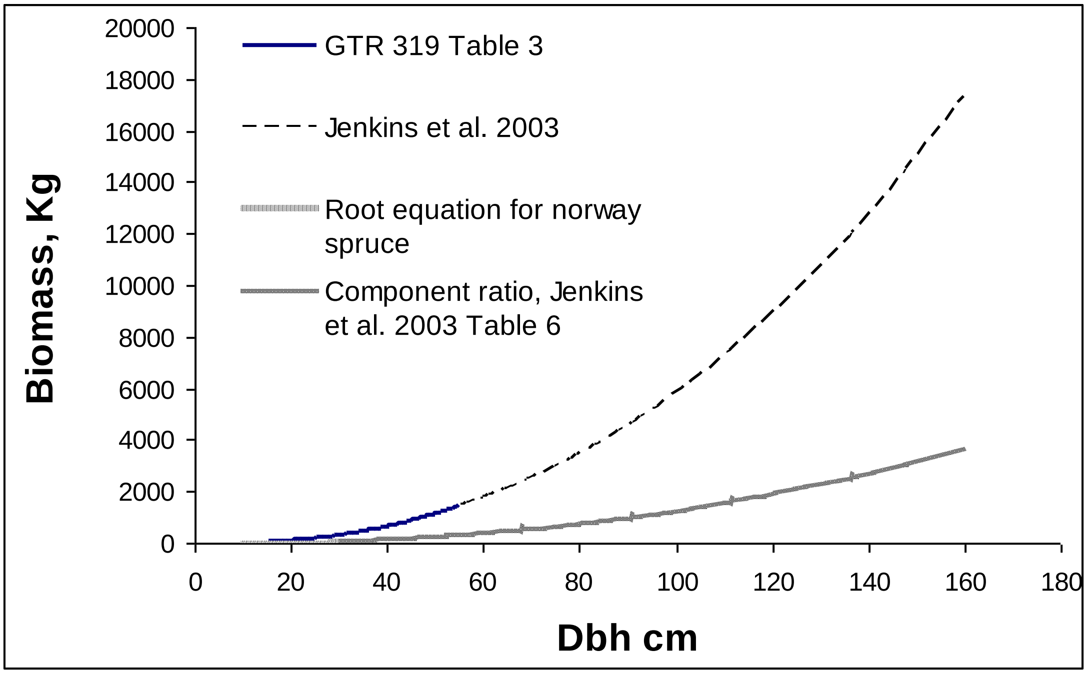

Figure 13. Above ground and below ground biomass responsive curves applied to sitka spruce. The same equations were applied to Alaska cedar and incense cedar.

Pacific madrone, *Arbutus menziesii*

There are two equations in GTR 319 for dead branches (BBD) and crown (BCT) branches, foliage, twigs that apply to dbh's between 2.54 to 63.5. A whole tree equation only applies to dbh's between 1 and 6 cm. Since these equations are incomplete for above-ground, and below-ground biomass the equation for red alder was used instead. The biomass curves, then, will be the same as in Figure 3. There may be a more appropriate alternative for estimating madrone biomass other than the equation for red alder, therefore, updating the software will be an ongoing priority when new information is available and time can be devoted to the effort.

Grand fir and white fir

There are 2 stem (wood and bark) equations in GTR319, Table 3 for grand fir through a dbh range of 0 to 10.16 and a crown equation for a dbh range of 2.54 to 30.48. Given the small dbh range applicability for these equations the above ground biomass and root equations from the White fir set were used to estimate biomass for grand fir.

Four equations for AGBM are from GTR319, Table 3 for a dbh range of 7 to 98. The Jenkins et al. (2003) Table 4 equation for True fir/hemlock was used for dbh's between 2.5 and 7. The straight line from zero to 2.5 was used for dbh's less than 2.5. The root equation from Douglas fir was used for roots. A curve for the component root equation for softwoods from Jenkins et al. (2003) is also shown in Figure 9.

The biomass estimates using the white fir equations appear to be very high. For example at a dbh of 80 cm the Douglas fir equations produce an aboveground biomass estimate of 5202 kg whereas the white fir equations produce an estimate more than twice that, 17,596 kg. The aboveground biomass estimate using the equation from Jenkins et al. (2003) table 4 for True fir/hemlock is 4301 kg. Therefore, the equations for Douglas-fir were used for grand fir and white fir as the next best alternative.

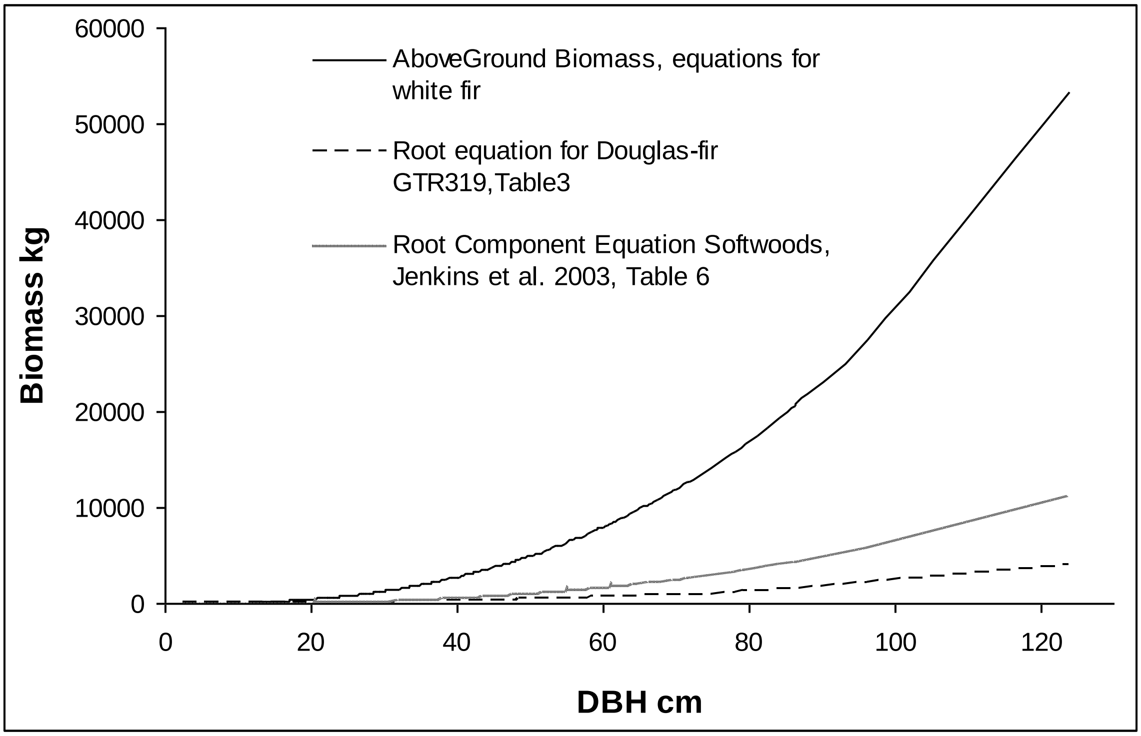

Figure 14. Aboveground and root biomass response curves for grand fir and white fir.

Ponderosa pine, *Pinus ponderosa*

There are 6 equations from Gholz et al. that were used in sum to estimate AGBM through a dbh range of 15.5 to 79.5. The Jenkins et al. 2003, Table 4 equation for Pine was used for dbh's from 2.5 to 15.5 and a straight line from zero for dbh's less than 2.5.

There were two equations applied for estimating root biomass. Both equations come from GTR319 for Monterey pine because there isn't an equation for Ponderosa pine roots. The first equation is valid between dbh's of 5 to 20 cm and the second equation for dbh's between 39 and 65 cm. The first equation was applied to dbh's between 20 and 39 cm for the sake of convenience. The response curve for the component equation for softwood roots from table 6 of Jenkins et al. (2003) is shown in Figure 10 along with the two response curves for montery pine. Results show that estimates vary between equations with the root component equation producing higher estimates in the larger DBH range.

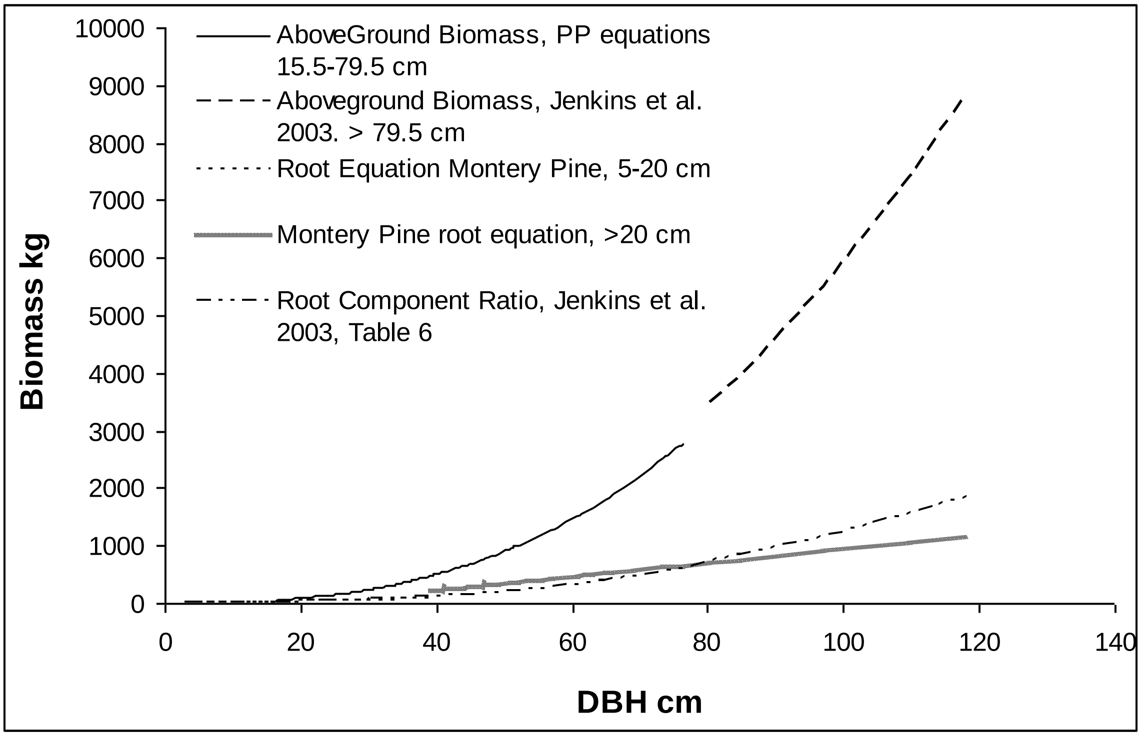

Figure 15. Aboveground and root biomass response curves for ponderosa pine.

Cherry, *Prunus spp*.; hawthorn, *Crataegus*

Three equations for chokecherry from GTR319, BST, BBT, and BFT were used to estimate aboveground biomass through a dbh range of 2.54 to 15.24. The Jenkins et al. (2003) equation for AGBM of mixed hardwood was used for dbh's outside of this dbh range. The GTR319 equation for roots, BRT, were used through the complete dbh range. The Jenkins et al. (2003) equation.

The Jenkins et al. (2003) equation produced aboveground estimates much less than the GTR 319 equations at the cutoff dbh of 15 cm.

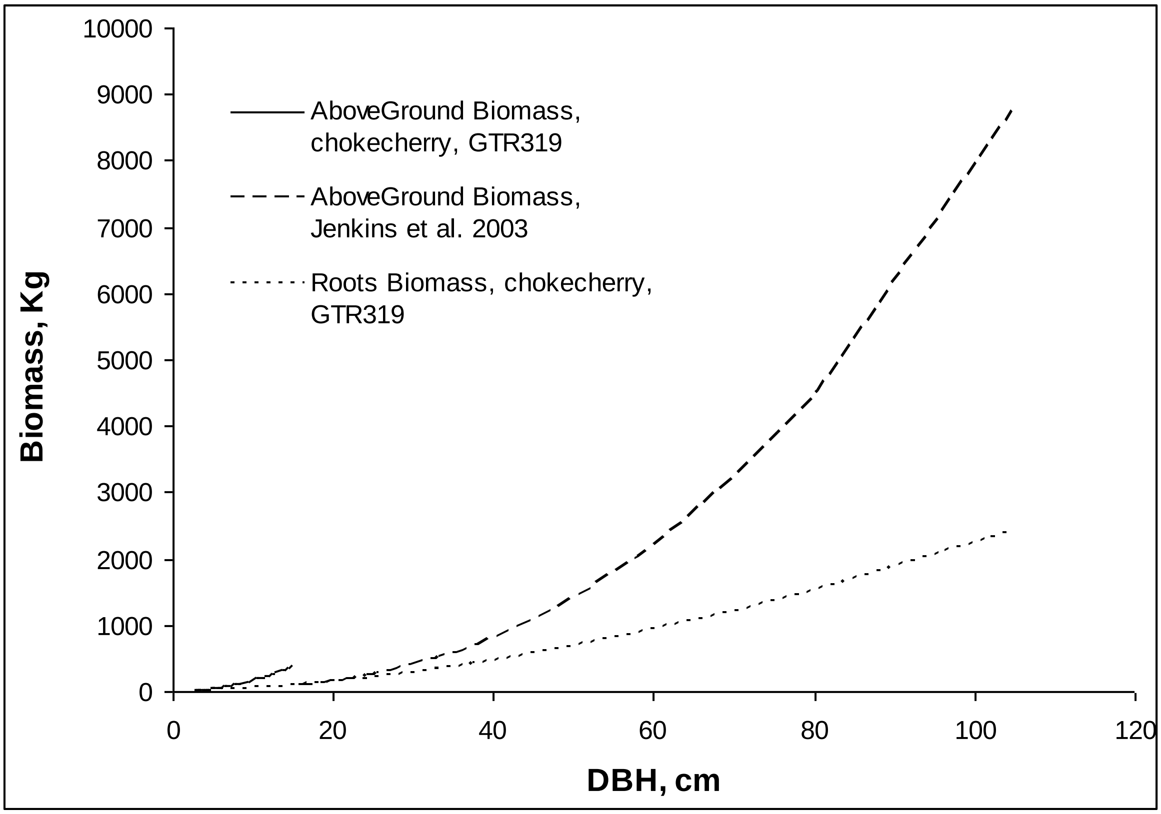

Figure 16. Above ground and root biomass response curves for Cherry (Prunus) and hawthron (Crataegus) species.

noble fir, *Abies procera*

The Gholz et al. 2003 equation set ranges from 18.8 to 111.0 dbh in cm. The Gholz equations were used for BFT, BBL, BSW and BSB. AGBM is the sum of these four components. For dbh measurements between 2.5 and 18.8 the equation from Jenkins et al. (2003), Table 4-True fir/hemlock, was used. For dbh measurements less than 2.5 cm the slope of the line between 0 dbh and the AGBM estimate for dbh of 2.5 was multiplied by dbh to estimate biomass.

The equation for roots is from GTR NE-319 and is the same equation as the Pseudotsuga menziesii BRT equation in Gholz et al. Total Biomass (TotBio) is the variable for sum of BRT and AGBM.

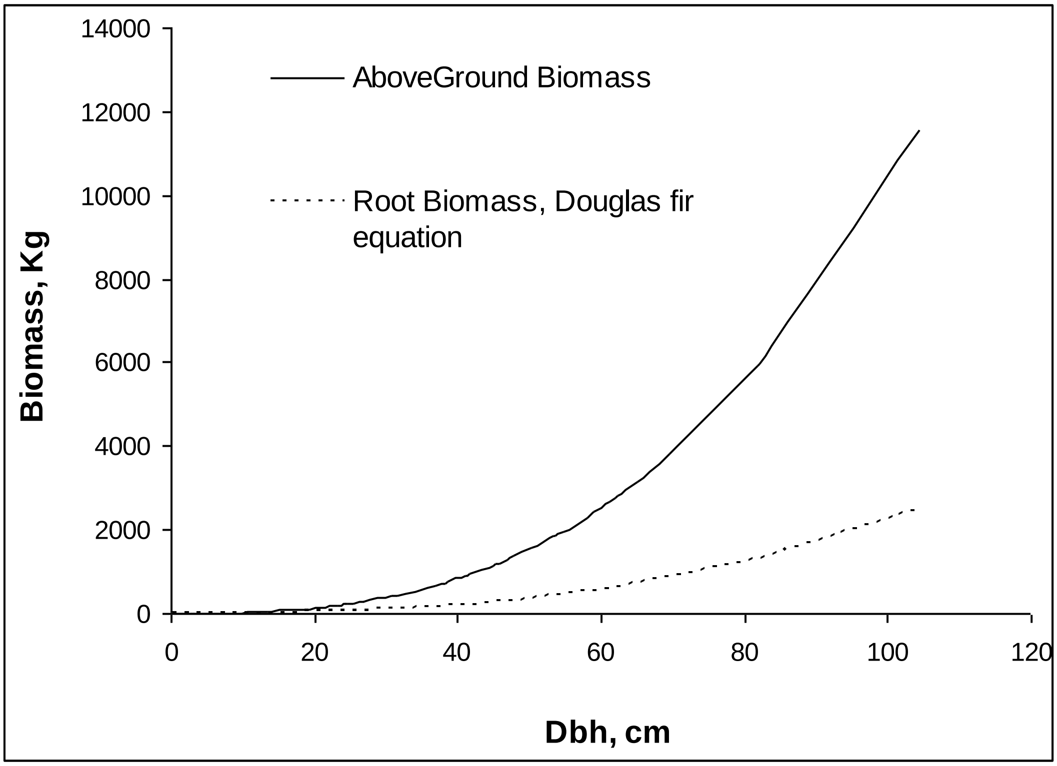

Figure 17. Above ground and root biomass estimate curves for noble fir. The Root curve was produced using the equation for Douglas fir.

Pacific silver fir, *Abies amabilis,*

The Gholz et al. equations contain BFT, BBL, BSW, and BSB for a dbh range of 11.7 to 90.4. The sum of these individual tree part calculations were then used as an estimate of above ground biomass (AGBM). For dbh measurements between 2.5 and 11.7 the equation from Jenkins et al. (2003), Table 4-True fir/hemlock, was used. For dbh measurements less than 2.5 cm the slope of the line between 0 dbh and the AGBM estimate for dbh of 2.5 was multiplied by dbh to estimate biomasss. The equation for roots is from GTR NE-319 and is the same equation as the Pseudotsuga menziesii BRT equation in Gholz et al. Total Biomass (TotBio) is the variable for sum of BRT and AGBM.

Sugar pine and Jack pine, *Pinus lambertiana, Pinus banksiana*

Four equations from Gholz et al. comprise the AGBM summation for a dbh range from 20.6 to 43.3. Jenkins et al. 2003 is used for dbh's from 2.5 to 20.6 and above 43.3. The straight line from zero is used for dbh's less than 2.5. There was not a root equation for sugar pine but there was one for Monterey pine in GTR319, Table 3 for dbh's at least 5 cm. The curve from the component root equation of Jenkins et al. (2003) Table 6 is also shown in Figure 14 and will be used as the default equation. The straight line from zero was used for dbh's less than 5 cm.

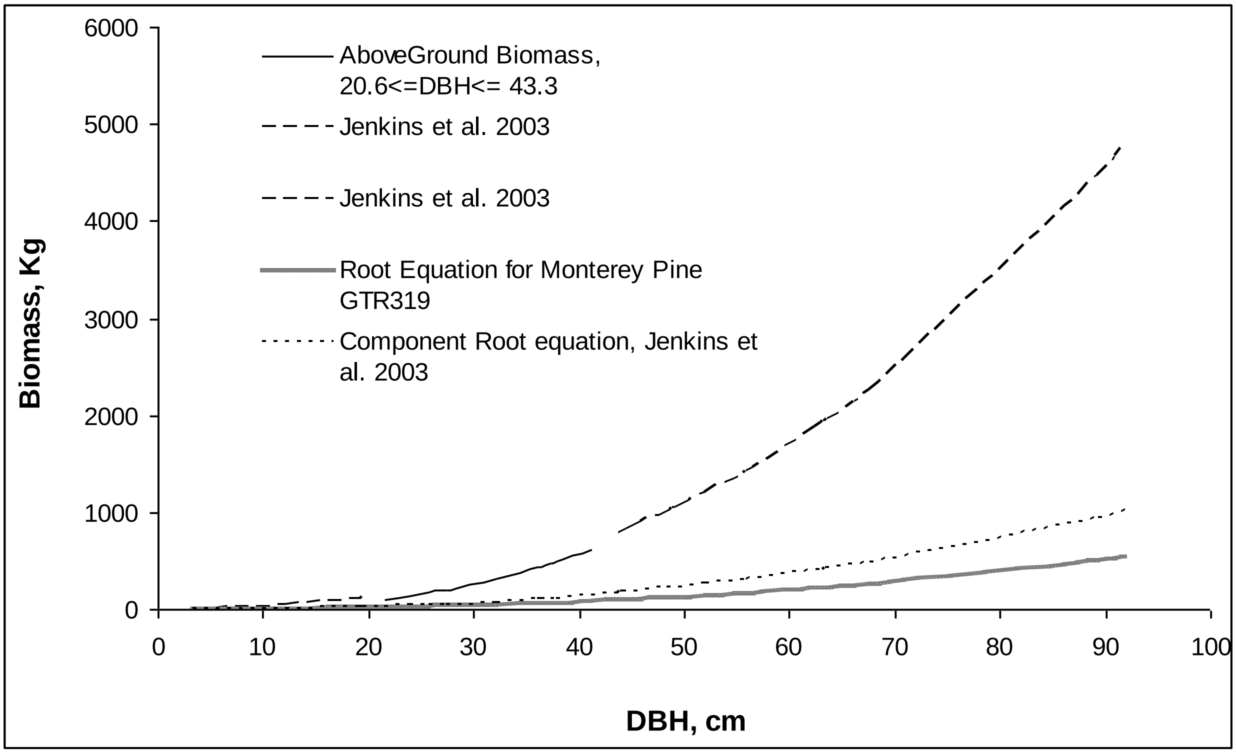

Figure 18. Aboveground and root biomass for sugar pine and jack pine. A curve produced by the root equation for Monterey pine is shown along with the curve produced by the component root equation from Jenkins et al. (2003).

Cottonwood, *Populus species*

The equation for cottonwood BST from Table 3 of GTR 319, corresponding to a dbh range of 2.54 to 50.8 (in biomass = 0.173 + 2.6709 * (ln(dia))), produces unrealistically high values. GTR 319 offers two other equations for BST for a dbh range between 12.5 and 55 but these equations also produce questionable values. The best alternative is to use the Jenkins et al. (2003) equation for aspen/alder/cottonwood/willow through the full dbh range. Root biomass was estimated using the component equation from Table 6 of Jenkins et al. 2003.

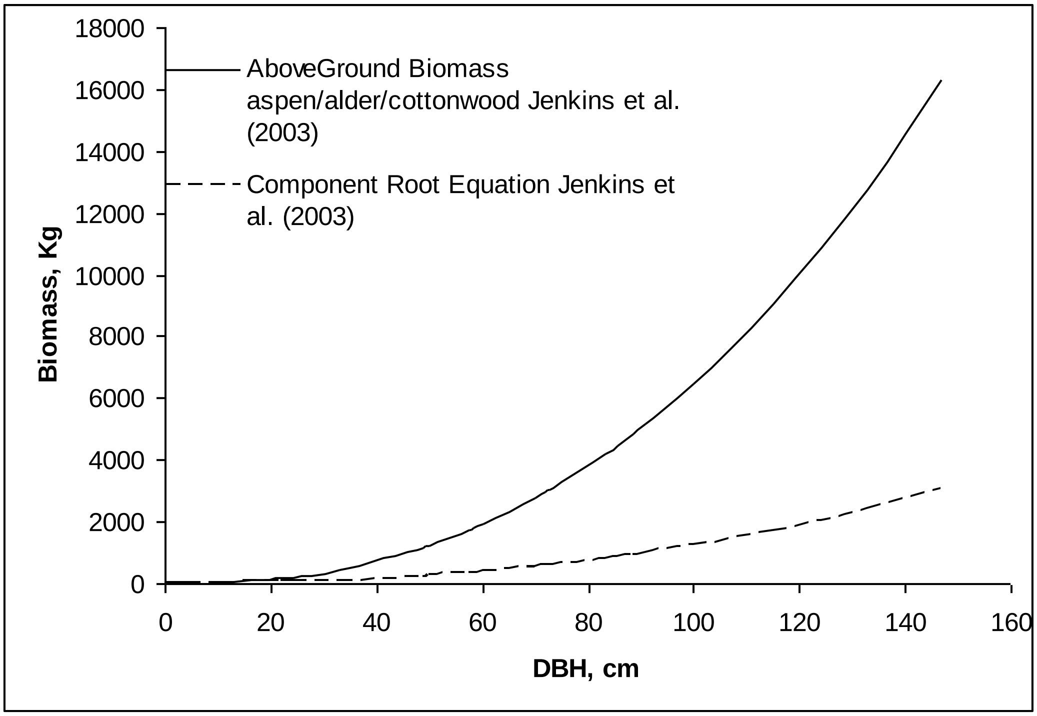

Figure 19

Coast redwood, *sequoia sempervirens*

There are three stem equations in GTR 319 for sequoia for a dbh range of 96 to 614. Few trees in the FIA Oregon database fall within this dbh range category. Therefore, the equations for Douglas fir were used.

Tanoak, *Lithocarpus densiflorus*

The western Oregon FIA database for private forest land contained 19 records for tanoak with the largest dbh at 11 cm. There is an equation for whole tree above ground for a dbh range of 1 to 5 cm in GTR 319. However, this equation produced unreasonably small values for biomass. The Jenkins et al. equation for aboveground biomass for hard maple/oak/hickory/beech was used instead. The component root equation from Table 6 of Jenkins et al. 2003 was used to estimate root biomass. The results from application of the two equations to the 19 FIA record is shown in Figure 15.

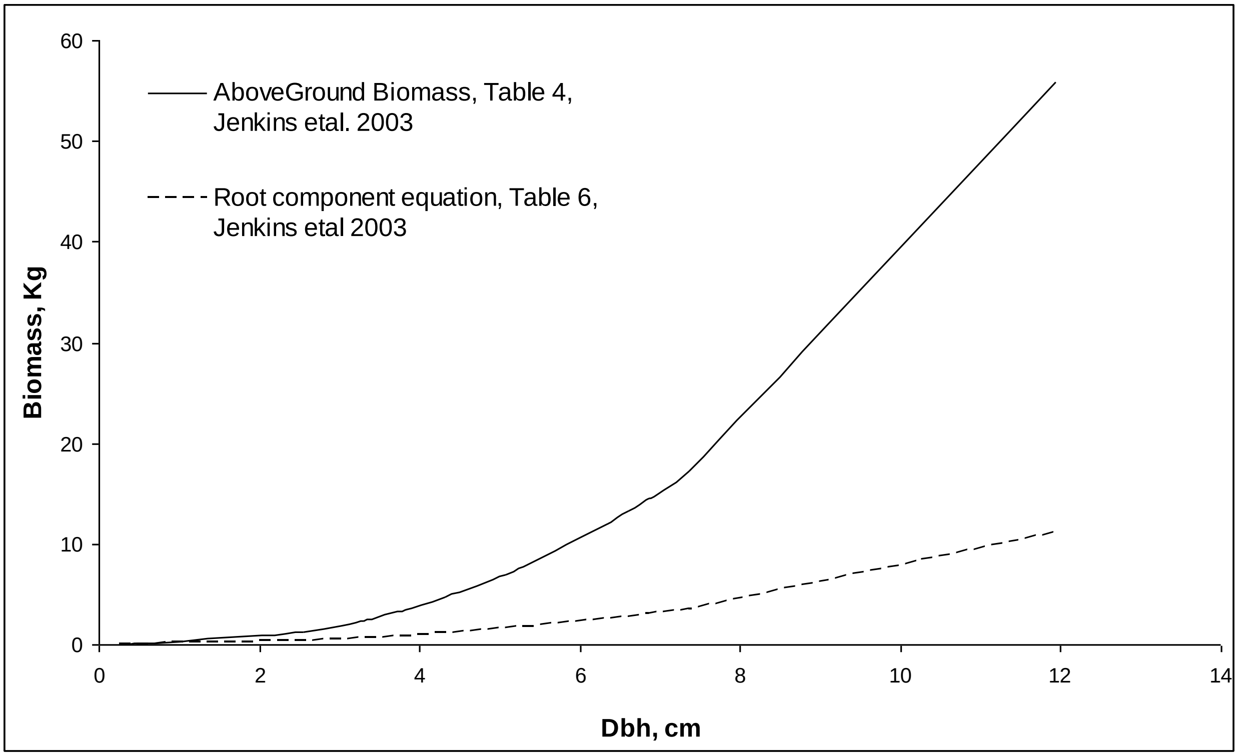

Figure 20. Aboveground biomass response curves for tanoak.

Mountain hemlock, *Tsuga mertensiana*

There are 5 equations in Gholz et al. through a dbh range from 17 to 76.2 for AGBM. The Jenkins et al. (2003) Table 4 equation for True fir/hemlock was used for dbh’s between 2.5 to 17 and above 76.2. A straight line was used for dbh’s less than 2.5. The root equation is the same as for western hemlock. An equation for root biomass was not available; therefore, the equation from Douglas fir roots was used. The western Oregon FIA database for private forestland contained no records for mountain hemlock.

Lodgepole pine and knobcone pine, *Pinus contorta, Pinus attenuata*

Gholz et al. has 3 equations BFT, BLB, and BSB within a dbh range of 2.5 to 28.7 but the equation was applied to all trees. There were 14 records for lodgepole pine in the western Oregon FIA database for private forestland with the largest dbh at 47.5 cm. These are summed to estimate above-ground-biomass (AGBM). The root equation comes from GTR319, Table 3 and uses basal area instead of dbh.

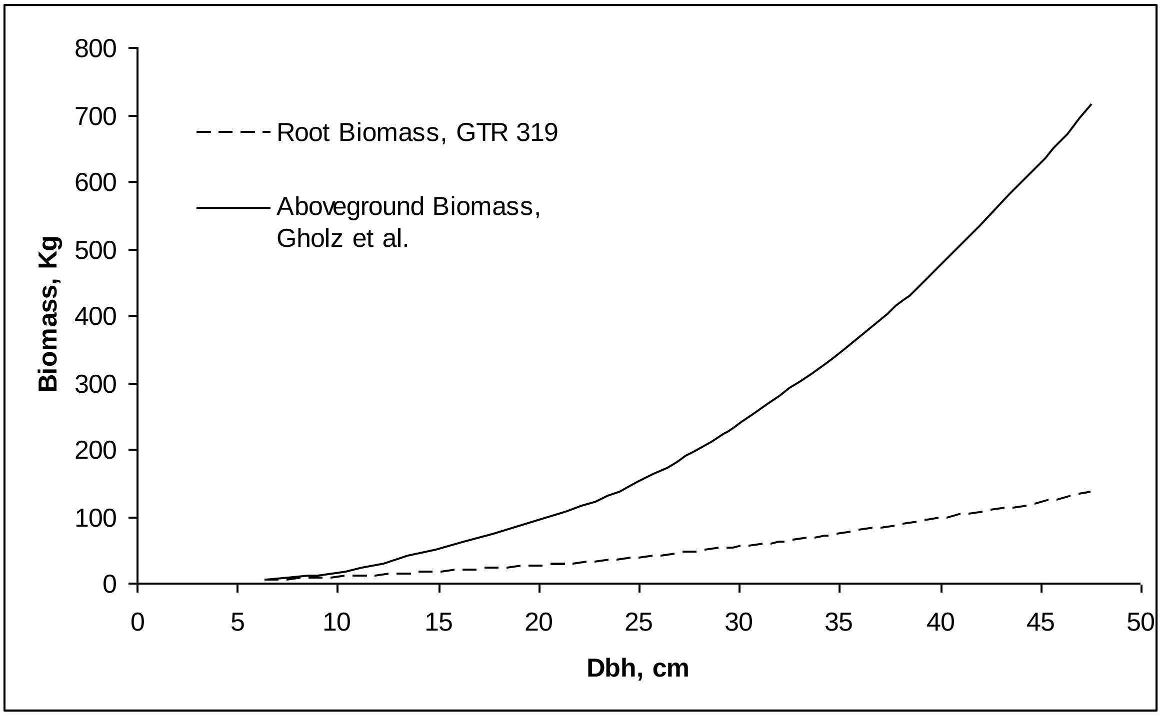

Figure 21. Above ground and root biomass estimates for lodgepole pine.

Engelmann spruce

Four equations, BSW,BSB,BBT, and BFT came from GTR319 for a dbh range of 4 to 76. The Jenkins et al. (2003) equation was used for dbh's from 2.5 cm and a straight line from zero to 2.5. The root equation was for the general spruce listing in GTR319.

Pacific dogwood, *Cornus nuttalli*

The equation from Jenkins et al. (2003) for mixed hardwood was used. A straight line was used for dbh's < 2.5 cm.

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