An analysis of biomass estimation techniques for two oak species at Black Rock Forest in Cornwall, New York

by Madeline Hirshan

Advisor: Peter Bower, Barnard Environmental Science

Abstract

All tree species within forests are capable of storing carbon. The ability of trees to harness carbon and incorporate it into their biomass may provide a significant carbon sink with current conditions of climate change. Therefore it is important to observe how much carbon forests can store in order to design future mitigation strategies. This project, which was set at Black Rock Forest (BRF) Consortium in New York State, aimed to understand how much dry aboveground biomass two oak species, chestnut oak (*Quercus prinus*) and red oak (*Quercus rubra*), contained in order to further estimate the total amount of carbon uptake by these tree species. Thirteen years of data from both species that have been felled were utilized for this project and additional trees were felled to present a more representative sample of different diameter trees. Oaks were studied because they represent a majority of the tree species in the forest comprising greater than 80% of the trees. The actual weights of the felled trees were compared to the outputs from species-specific allometric equations, a general hardwood equation, and original equations which were calculated using actual BRF data for each species. Trees were selected at a range of diameters (DBH, diameter at breast height) to determine the validity of these equations based on different sizes of trees. The equations were compared to the measured data to determine the equation which best estimates biomass for each species. There was more variability in the accuracy of the three equations tested for *Q. prinus* trees while the predictions were more similar across equations for *Q. rubra* trees. The implications for this project include the ability to accurately measure forest carbon in order to monitor changes in biomass over time.

Introduction

Average global temperatures have increased approximately 0.55˚C since the 1970s (IPCC 2007) and increasing concentrations of carbon dioxide in the atmosphere may be resulting in the rise of temperatures thus accelerating climate change. As global forest cover consists of nearly 4000 million hectares, the ability of forests to sequester large amounts of carbon may be especially important in light of changes in climate (IPCC 2007). Forests play an important role in their ability to store large amounts of carbon (Dixon et al. 1994) and the carbon stored in the terrestrial biosphere can be regulated if necessary due to changing conditions which may allow for mitigation (Birdsey 1992). The IPCC 2007 report documents that between the years 1993 and 2003, the terrestrial biosphere had sequestered about 3,300 $MtCO_2$/year. With global warming as a pressing issue, it is necessary to understand how natural systems can reduce the amount of carbon dioxide in the atmosphere as atmospheric CO_2 has increased up to 25% in the past 100 years (Houghton et al. 1983).

Forests in the Northern Hemisphere have been considered carbon sinks, but the extent of their uptake of carbon and the particular location of sinks are still debated (Goodale et al. 2002). Trees invest energy into carbon storage in its wood, stumps, branches, and other components. However, carbon can be lost due to fires, insect invasions, and tree death (Myneni et al. 2001). Additionally, differences in terrestrial land use have had an effect on the resulting carbon flux (Houghton et al. 1983). The re-growth of cleared forests and soils store carbon while the clearing of forests for agriculture releases carbon into the atmosphere (Houghton et al. 1983). With increasing temperatures and atmospheric CO_2 levels, it has become difficult to understand forest responses to climate change, in particular, their ability to act as carbon sinks on a global scale, as well as their effects on local environments (Graham et al. 1990). When studying correlations between carbon dioxide and temperature, it was determined that responses to climate change tend to be dependent on geographic locations (Braswell et al. 1997).

The amount of carbon in tree biomass can range from 45 to 50 percent (Birdsey 1992). Although trees can incorporate atmospheric CO_2 into their biomass, it has been shown that young forests store carbon at faster rates than do older, more mature forests (Birdsey et al. 1993). The ability of a forest to act as a carbon sink may depend on many factors such as the age of the stand, as younger forests tend to accumulate more carbon than old-growth forests which may reach a saturation point (IPCC 2007). The amount of carbon that is able to be stored depends on whether the tree's biomass has reached its maximum value (Brown et al. 1997). Understanding the means by which the terrestrial environment had stored carbon in the past, whether by increases in plant growth (due to CO_2 levels in the atmosphere), or by desertion of agricultural lands, can assist in making predictions about carbon uptake in the future (Albani et al. 2006).

Dry aboveground biomass provides an important estimate of carbon pools and fluxes at global scales (Jenkins et al., 2004). In order to estimate forest aboveground biomass, regression equations have been derived to calculate biomass based on diameter at breast height (DBH) (Tritton and Hornbeck 1982, Jenkins et al. 2004). These allometric equations are modified for individual species of trees. However, there can possibly be error associated with using previously published equations as differences in geographic location may play a role (Jenkins et al. 2003). There are some factors which have not been incorporated into allometric equations which may increase error and uncertainty. Some of these factors include a lack of measurements of large diameter trees with a diameter greater than 60 cm, and a lack of site specific equations that account for changes in species composition, geographic characteristics, and responses to environmental changes (Brown 2002). Additionally, the age of tree stands may have a significant impact on obtaining accurate allometric models for tree biomass (Fatemi et al. 2011). Variability in tree density and canopy structure may also influence the biomass and carbon storage of these tree species (Fatemi et al. 2011). There would be better estimates of biomass and carbon storage if there were more allometric equations that estimated biomass of small diameter trees as well (Singh et al. 2011). Therefore, although allometric equations provide good estimates of biomass, in order to obtain the most accurate estimates of biomass, it is important to choose equations that best reflect the specific tree species and the site location.

The purpose of this project was to find the best method for quantifying dry aboveground biomass for red oak (*Quercus rubra)* and chestnut oak (*Quercus prinus*) species in Black Rock Forest Consortium, located in the Hudson Highlands in New York State. Researchers have used species-specific allometric equations to study how biomass changed with time in Black Rock Forest (Schuster et al. 2008). This project aimed to test the validity of the equations that were chosen to be representative for Black Rock Forest, which were used in Schuster *et al.* 2008. We sought to determine whether the species-specific equation (Brenneman et al., 1978), the general hardwood equation (Monteith, 1979), or the newly derived BRF equation was best for estimating dry aboveground biomass for both oak species.

Methods

Site Description

This project was set at Black Rock Forest Consortium located in the Hudson Highlands in Cornwall, New York. Black Rock Forest (BRF) is located about 60 miles north of New York City (Fig. 1). The Consortium, which is comprised of many academic institutions such as Barnard College and Columbia University, was formed in 1989 and is a center for science, education, and research (Buzzetto-More, 2006). The forest is approximately about 1,550 hectares and the most predominate tree species are oaks comprising greater than 80% of the trees in the forest (Schuster et al. 2008).

Tree Felling

In order to test the validity of the previously derived allometric equations which were utilized to measure dry aboveground biomass at BRF, eleven chestnut oak (*Quercus prinus)* trees, and twelve red oak (*Quercus rubra)* trees were felled between the years 2000 and 2013. The data collected for both *Q. prinus* and *Q. rubra* were also used to generate a site-specific equation for BRF. Allometric equations are regression equations that convert tree diameter at breast height (DBH, 1.37 meters) to dry aboveground biomass in kilograms.

Each tree that was selected was chosen based on its diameter at breast height, which is a standard measurement (Jenkins et al. 2004). The diameter at breast can be measured using a tape measure that converts tree circumference into a diameter. This measurement is taken at the standard height of 1.37 meters. A variety of trees with different diameters were selected for both tree species. Each tree was cut down using a chainsaw. The tree was then measured to determine its height. Next, each tree was cut into smaller pieces using the chainsaw and every piece of the tree was weighed including the trunk, branches, and leaves. In order to obtain the tree's total wet weight, each portion of the tree was tied with ropes and hung from a scale on a tractor (Fig. 2). The scale measures the weight of each piece in pounds with two pounds per line increment. The sum of the weights gathered from all of the sections of the entire tree encompasses the tree's wet weight. A tree "cookie" (slice of a tree) from each tree was cut into quarters, stored in a plastic bag, and brought back to the lab where each was weighed. The quarters were dried in a drying oven at 80˚C. Once the quarters were dry, a final weight was measured using a scale. Finally, a drying factor was calculated (final weight/initial weight). The tree's wet weight (sum of felled tree weight) was multiplied by the drying factor to determine the dry weight of the tree. This weight is the dry aboveground biomass measured in kilograms. This measured value was later compared to the outputs from the allometric equations.

Allometric Equations

There is a list of allometric equations that have been selected to represent the trees at Black Rock Forest (Schuster et al. 2008). The equations that have been used are Brenneman's individual red oak and chestnut oak equations and the Monteith general hardwood equation. The specific red oak equation is (2.4601*(DBH)^2.4572)/2.205 and the specific chestnut oak equation is (1.5509*(DBH^2.7276))/2.205 (Brenneman et al. 1978). The general hardwood is 5.5247-(0.3352*DBH*25.4)+(0.006551*DBH^2*25.4*25.4) (Monteith 1979). Unique allometric equations were also derived using a previously published model (Jenkins et al. 2003).

Statistical Analysis

The collected measurements from the tree felling were compared to the outputs from the allometric equations including the species specific equations and the general hardwood equation. Additionally, the two previously derived equations were compared to a site-specific equation for BRF. Statistical analyses including the sum of squared residuals were calculated using Microsoft Excel. Additionally, correlation statistics and paired t-test comparisons were performed in STATA statistical software to understand the relationships between the measured weight of the trees and the results from the equations. Normal quantile plots were also generated in STATA to determine how normally distributed the data were in order to perform the paired t-test. It was assumed that the data were normally distributed enough to continue with the paired t- test. To generate the new allometric equations, the add-in "Solver" was used in Microsoft Excel. We also made observations to understand if there are differences in the accuracy of the equations for small and large diameter trees.

Results

The sample size for *Q. prinus* was eleven trees and the diameters of the felled trees ranged from 6.8 inches to 20.3 inches. Increases in measured dry weight were associated with a rise in predicted aboveground biomass for the *Q. prinus* species-specific equation from Brenneman et al. 1978 (Fig. 3, 4a; R^2=.912). The species-specific equation outputs are greater than the measured data (Table 1; $p<.05$). Increases in *Q. prinus* dry weight were also associated with rises in predicted dry weight when using the general hardwood equation from Monteith et al. 1979 (Fig. 3, 4b; R^2=.937). A specific allometric equation for *Q. prinus* utilizing data collected from BRF was created to minimize the squared residuals in between measured and predicted data thus constructing an equation specifically tailored for BRF given the collected data. The data yielded: $\text{Biomass}= \text{Exp}(-.3181+1.965\ln(\text{DBH}))$. The data collected for DBH (diameter at breast height) were entered into this equation and compared to the actual measured dry weights of the felled *Q. prinus* trees. Increases in the measured data corresponded with an increase in the predicted values (Fig. 3, 4c; R^2= .940). When error in the form of residuals associated with the equations was compared between the three equations, there was a larger sum of squared residuals value with the Brenneman equation than with either the Monteith general hardwood equation or the BRF equation (Fig. 5). The estimates of the general hardwood equation and the BRF equation are not significantly different from the measured values (Table 1; $p>.05$).

The sample size for *Q. rubra* was twelve and the diameters of the felled trees ranged from 5 to 18.9 inches. Increases in measured dry weight for *Q. rubra* corresponded to increases in predicted dry weight with the species specific equation, the general hardwood equation, and the BRF specific equation (Fig. 6, 7a-c; R^2=.966, .961, and .966 respectively). A specific biomass equation was derived for *Q. rubra* trees at BRF and yielded: Biomass= Exp(-2.5637+2.57925ln(DBH)). This equation was calculated using BRF data to minimize the squared residuals between individual data points. The DBH's of measured *Q. rubra* trees were inputted into this equation and compared with the species-specific equation derived from Brenneman et al. 1978, and the general hardwood equation from Monteith 1979. The sum of squared residuals was highest for the *Q. rubra* general hardwood equation which also had the largest sum of the squared residuals (Fig. 8). All three equation's estimates were not significantly different from the measured values (Table 2; $p>.05$). The general hardwood equation p-value is very close to being .05 and has a larger mean difference than the other two equations for *Q. rubra* (Table 2).

Discussion

The relationship between the actual dry weight and species-specific equation output for *Q. prinus* suggests that the species-specific allometric equation is relatively accurate for predicting biomass thus allowing for precise determinations of carbon storage in forests. However, the general hardwood and BRF equation predictions appear to follow the data with a better fit, with higher R^2 values. Additionally, the species-specific equation for *Q. prinus* is the only equation of the three for *Q. prinus* that is significantly different from the measured dry weights. On average, the Brenneman equation significantly overestimates the dry aboveground biomass which could potentially affect forest calculations of its carbon storage. This equation is accurate for *Q. prinus* trees below thirteen inches in diameter, however; it increases in error above thirteen inch diameters. This difference in accuracy based on diameter implies that the equation may be more accurate when determining biomass for smaller trees and a different equation may need to be utilized for *Q. prinus* trees above thirteen inches in diameter. Thus the species-specific equation may not be the most accurate equation to utilize for *Q. prinus*, particularly at larger diameters. However, more trees may need to be felled in order to see the exact diameter cut-off point. This result may suggest that the general hardwood equation may be more accurate than the specific *Q. prinus* equation, especially for larger trees. The BRF equation is more precise than the general hardwood equation. The explanation for this occurrence may be the fact that data which was used in the formation of the equation was gathered at BRF itself as opposed to another site.

The consistent results found from the allometry analysis of dry weight outputs compared to the predictions for *Q. rubra* suggest that the dry aboveground biomass of *Q. rubra* can be accurately predicted using the previously derived equations or the newly derived equation for BRF. The results also imply that *Q. rubra* biomass may be more accurately predicted using allometric equations than that of *Q. prinus* based on the data collected. These differences may be attributed to many factors including the applicability of the previously derived equations to be used in new regions (such as BRF), or possibly changes in the accuracy of the equations at larger tree diameters, which is observed with *Q. prinus*.

Unlike the previously derived equations, the newly derived equations utilize actual BRF data and calculate coefficients in a way to minimize the sum of squared residuals. Therefore, it is likely that as more data are collected, the equation will become a more accurate model. To calculate the most accurate, local allometric model, a large sample size is essential because there can be large spatial variations in carbon stocks across stands and forests (van Breugel et al. 2011). Perhaps there may be some error associated with the BRF equations due to the small sample size. Although calculating independent equations for every site may not be feasible, this approach would yield the most accurate data. However, generalized equations, which utilize field data from a specific site and can be implemented by other areas in a region, may be applicable for certain tree species (Pastor et al. 1984). It would be beneficial to determine if the equations selected for BRF are also applicable to surrounding areas perhaps representing the Hudson Highlands region. The implementation of the same set of equations between sites may reduce variations in biomass calculations caused by the equation itself, and allow for more accurate comparisons between sites (Pastor et al. 1984). An alternative approach that may be useful for establishing a more regional equation can encompass different factors relating to trees including wood density, height, and diameter which can prevent the use of tree destruction for sampling (Ketterings et al. 2001).

To further utilize these equations on a larger scale, other tree characters such as height classifications could be incorporated to reduce biases and improve estimates (Li and Zhao 2013). There is a uncertainty however, over the utility of incorporating tree height into allometric equations, and instead some researchers are in favor of the construction of a general allometric equation that can be a feasible measure in addition to providing accurate estimates (Montagu et al. 2005). This ability to construct a general regional equation however may vary based on tree species and site location. To best compare the validity and extent of the general equations best suited for BRF, it would be important to compare equations across regional scales and determining their accuracy (Ngomanda et al. 2014). Although allometric relationships are widely used and allow for forest monitoring of tree biomass using non-destructive methods, new methods of calculating national biomass estimates have been adopted which incorporate tree height and species volume. However, this new method estimates present carbon stocks that vary greatly from past allometric model estimates (Domke et al. 2012). Further research is required to construct the best methods to calculate carbon storage at larger scales that will provide the most accurate estimates. Differences may be due in part to necessary revisions of past equations which may now be more accurate in predicting aboveground biomass (Chojnacky et al. 2014).

There is great importance in determining the best method or allometric equation to use for measuring forest biomass and subsequent carbon storage. In Black Rock Forest it was determined that *Q. rubra* and *Q. prinus* trees are still able to store carbon, however changes in tree compositions and canopy status have the potential to significantly affect the sequestering capability of Black Rock Forest (Schuster et al. 2008), therefore it is important to monitor change in biomass over time. Although there may be variations between regions and forests, the equations that are utilized should be the most accurate for the specific forest and tree species. Because of the large global presence of forests which are able to function as carbon sinks, it is essential to be able to quantify and predict forest carbon storage as a mitigation strategy for climate change.

References

Albani, M., D. Medvigy, G. C. Hurtt, and P. R. Moorcroft. 2006. The contributions of land-use change, CO2 fertilization, and climate variability to the Eastern US carbon sink. Global Change Biology **12**:2370-2390.

Birdsey, R. A., A. J. Plantinga, and L. S. Heath. 1993. PAST AND PROSPECTIVE CARBON STORAGE IN UNITED-STATES FORESTS. Forest Ecology and Management **58**:33-40.

Birdsey, Richard A. 1992. Carbon storage and accumulation in United States forest ecosystems. Gen. Tech. Rep. WO-59. Washington D.C.: U.S. Department of Agriculture, Forest Service, Washington Office. 51p.

Braswell, B. H., D. S. Schimel, E. Linder, and B. Moore. 1997. The response of global terrestrial ecosystems to interannual temperature variability. Science **278**:870-872.

Brenneman, B.B., D. J. Frederick, W. E. Gardne, L. H. Schoenhofen, P. L. Marsh. 1978. Biomass of species and stands of West Virginia hardwoods. IN Proceedings, Central Hardwood Forest Conference II; 14-16 November 1978; West Lafayette, IN. pgs. 159-178.

Brown, S. 2002. Measuring carbon in forests: current status and future challenges. Environmental Pollution **116**:363-372.

Brown, S., P. Schroeder, and R. Birdsey. 1997. Aboveground biomass distribution of US eastern hardwood forests and the use of large trees as an indicator of forest development. Forest Ecology and Management **96**:37-47.

Buzzetto-More, N. 2006. The story of Black Rock: How an early sustainable forest spawned the American environmental movement and gave birth to a unique Consortium that links science, conservation, and education. *Hudson River Valley Review* 22(2): 109 – 121.

Chojnacky, D. C., L. S. Heath, and J. C. Jenkins. 2014. Updated generalized biomass equations for North American tree species. Forestry **87**:129-151.

Dixon, R. K., S. Brown, R. A. Houghton, A. M. Solomon, M. C. Trexler, and J. Wisniewski. 1994. CARBON POOLS AND FLUX OF GLOBAL FOREST ECOSYSTEMS. Science **263**:185-190.

Domke, G. M., C. W. Woodall, J. E. Smith, J. A. Westfall, and R. E. McRoberts. 2012. Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. Forest Ecology and Management **270**:108-116.

Fatemi, F. R., R. D. Yanai, S. P. Hamburg, M. A. Vadeboncoeur, M. A. Arthur, R. D. Briggs, and C. R. Levine. 2011. Allometric equations for young northern hardwoods: the importance of age-specific equations for estimating aboveground biomass. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere **41**:881-891.

Goodale, C. L., M. J. Apps, R. A. Birdsey, C. B. Field, L. S. Heath, R. A. Houghton, J. C. Jenkins, G. H. Kohlmaier, W. Kurz, S. R. Liu, G. J. Nabuurs, S. Nilsson, and A. Z. Shvidenko. 2002. Forest carbon sinks in the Northern Hemisphere. Ecological Applications **12**:891-899.

Graham, R. L., M. G. Turner, and V. H. Dale. 1990. HOW INCREASING CO2 AND CLIMATE CHANGE AFFECT FORESTS - AT MANY SPATIAL AND TEMPORAL SCALES, THERE WILL BE FOREST RESPONSES THAT WILL BE AFFECTED BY HUMAN ACTIVITIES. Bioscience **40**:575-587.

Houghton, R. A., J. E. Hobbie, J. M. Melillo, B. Moore, B. J. Peterson, G. R. Shaver, and G. M. Woodwell. 1983. CHANGES IN THE CARBON CONTENT OF TERRESTRIAL BIOTA AND SOILS BETWEEN 1860 AND 1980 - A NET RELEASE OF CO2 TO THE ATMOSPHERE. Ecological Monographs **53**:235-262.

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

Jenkins, J. C., D. C. Chojnacky, L. S. Heath, and R. A. Birdsey. 2004. Comprehensive Database of Diameter-based Biomass Regressions for North American Tree Species. General Technical Report NE-319, United States Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, Pennsylvania, USA.

Ketterings, Q. M., R. Coe, M. van Noordwijk, Y. Ambagau, and C. A. Palm. 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. Forest Ecology and Management **146**:199-209.

Li, H. K., and P. X. Zhao. 2013. Improving the accuracy of tree-level aboveground biomass equations with height classification at a large regional scale. Forest Ecology and Management **289**:153-163.

Montagu, K. D., K. Duttmer, C. V. M. Barton, and A. L. Cowie. 2005. Developing general allometric relationships for regional estimates of carbon sequestration - an example using Eucalyptus pilularis from seven contrasting sites. Forest Ecology and Management **204**:113-127.

Monteith, D. B. 1979. Whole-tree weight tables for New York. AFRI Research Report 40, State University of New York, Syracuse, NY, 40 p.

Myneni, R. B., J. Dong, C. J. Tucker, R. K. Kaufmann, P. E. Kauppi, J. Liski, L. Zhou, V. Alexeyev, and M. K. Hughes. 2001. A large carbon sink in the woody biomass of Northern forests. Proceedings of the National Academy of Sciences of the United States of America **98**:14784-14789.

Nabuurs, G.J., O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, O. Krankina, W.A. Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.J. Sanz Sanchez, X. Zhang, 2007: Forestry. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ngomanda, A., N. L. E. Obiang, J. Lebamba, Q. M. Mavouroulou, H. Gomat, G. S. Mankou, J. Loumeto, D. M. Iponga, F. K. Ditsouga, R. Z. Koumba, K. H. B. Bobe, C. M. Okouyi, R. Nyangadouma, N. Lepengue, B. Mbatchi, and N. Picard. 2014. Site-specific versus pantropical allometric equations: Which option to estimate the biomass of a moist central African forest? Forest Ecology and Management **312**:1-9.

Pastor, J., J. D. Aber, and J. M. Melillo. 1984. Biomass prediction using generalized allometric regressions for some northeast tree species. Forest Ecology and Management **7**:265-274.

Schuster, W. S. F., K. L. Griffin, H. Roth, M. H. Turnbull, D. Whitehead, and D. T. Tissue. 2008. Changes in composition, structure and aboveground biomass over seventy-six years (1930-2006) in the black rock forest, Hudson highlands, southeastern New York state. Tree Physiology **28**:537-549.

Singh, V., A. Tewari, S. P. S. Kushwaha, and V. K. Dadhwal. 2011. Formulating allometric equations for estimating biomass and carbon stock in small diameter trees. Forest Ecology and Management **261**:1945-1949.

Tritton, L.M., and J.W.Hornbeck. 1982. Biomass Equations for Major Tree Species of the Northeast. General Technical Report NE-69. United States Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Broomall, Pennsylvania, USA.

van Breugel, M., J. Ransijn, D. Craven, F. Bongers, and J. S. Hall. 2011. Estimating carbon stock in secondary forests: Decisions and uncertainties associated with allometric biomass models. Forest Ecology and Management **262**:1648-1657.

Figure 1. Map of Black Rock Forest. This map shows the location of Black Rock Forest in comparison to New York City. *Image taken from* http://www.blackrockforest.org/docs/about-the-forest/the-forest/LocationMap.html

Figure 2. Tractor holding the scale used to measure felled trees. This picture shows the method of how the entirety of each tree is weighed. Each piece was suspended from the scale to get the tree wet weight.

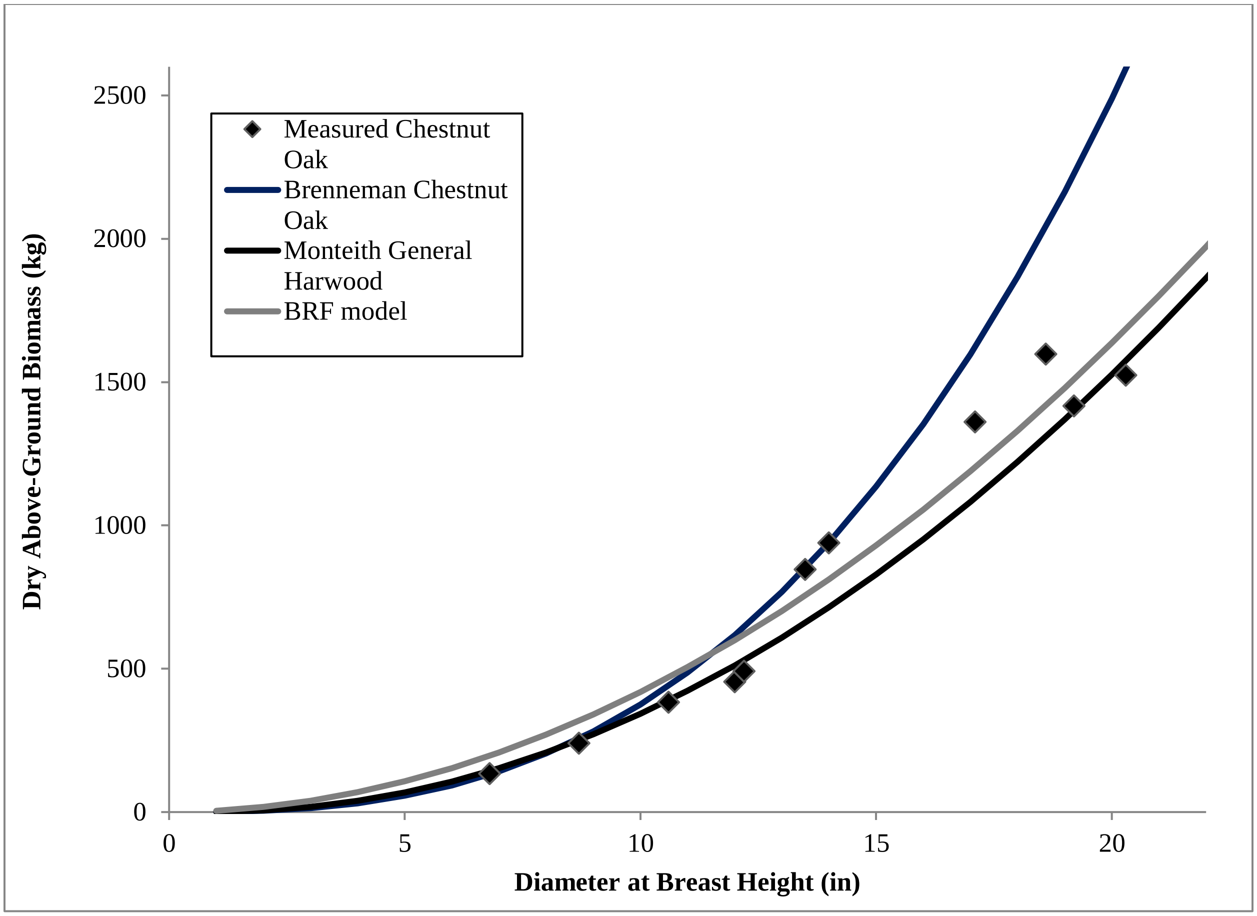
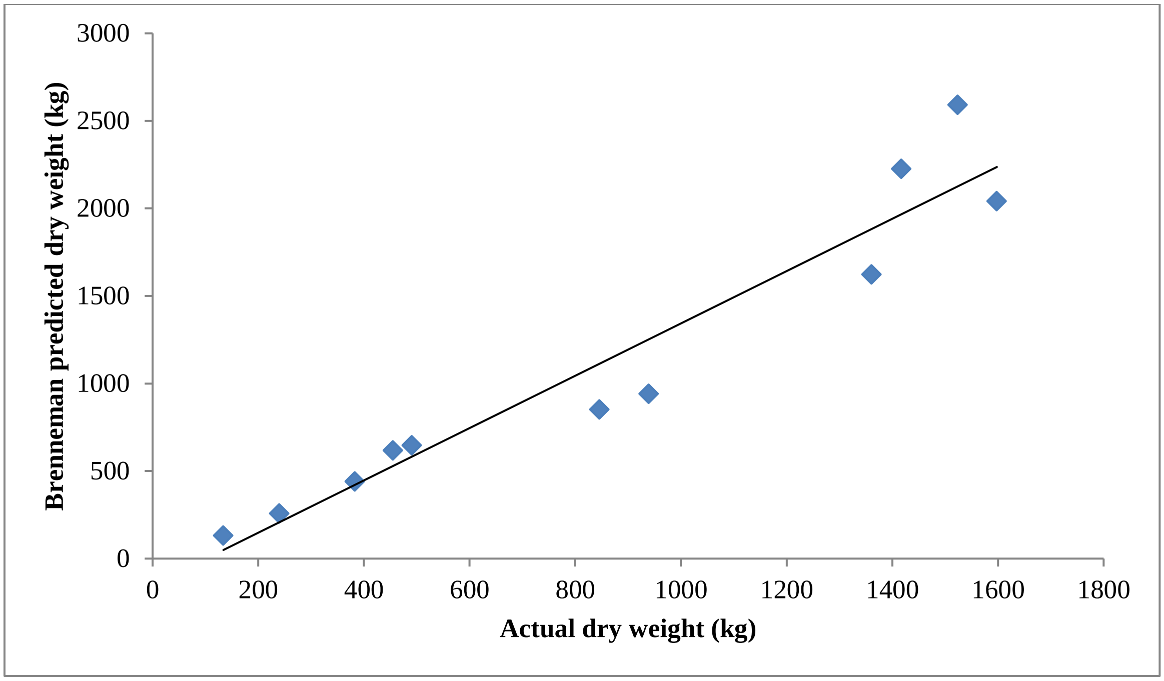


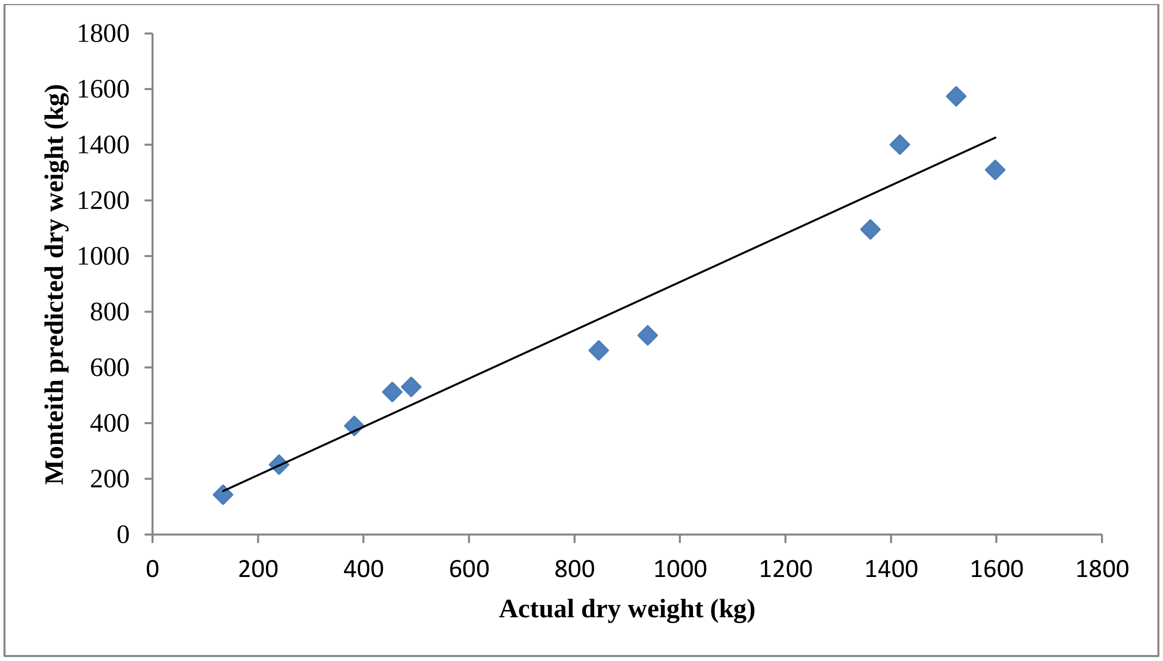
Figure 3. Plot of *Q. prinus* measured dry weight and the outputs from the allometric equations. The data points represent the data from the felled trees, diameter at breast height plotted against dry aboveground biomass. The lines represent outputs from the allometric equations at every given diameter. The Brenneman specific *Q. prinus* equation is (1.5509*(DBH^2.7276))/2.205, the Monteith general hardwood equation is Biomass=(5.5247-(0.3352*DBH*25.4)+(0.006551*DBH^2*25.4*25.4) and the BRF allometric equation for *Q. prinus* is Biomass= Exp(-.3181+1.965ln(DBH)),

a)



Brenneman predicted dry weight (kg)
3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
1200
1400
1600
1800
Actual dry weight (kg)

b)



Monteith predicted dry weight (kg)
1800
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
Actual dry weight (kg)

c)

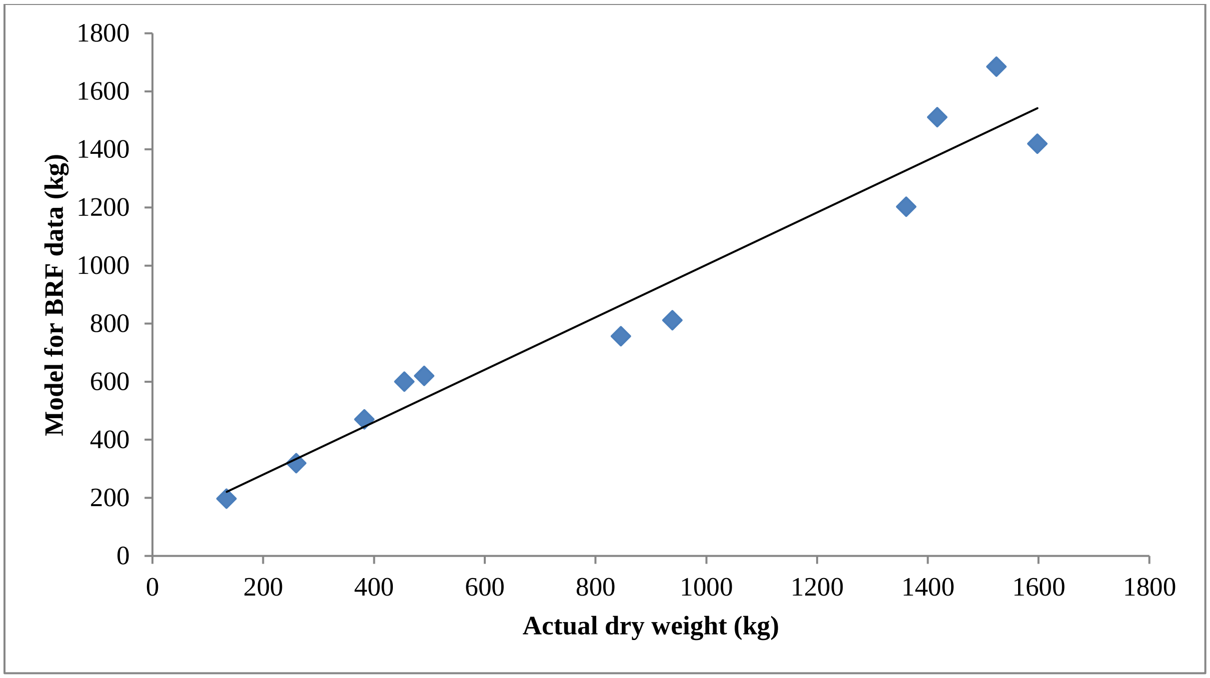


Figure 4. Correlation plots for determining best fit model for *Q. prinus*. These plots were used to calculate the R^2 in determining the best fit model for *Q. prinus*. a) *Q. prinus* species-specific equation plotted against actual dry weight (R^2=.91). b) General hardwood equation plotted against actual dry weight for *Q. prinus* (R^2=.94). c) BRF equation for *Q. prinus* plotted against actual dry weight (R^2=.94).

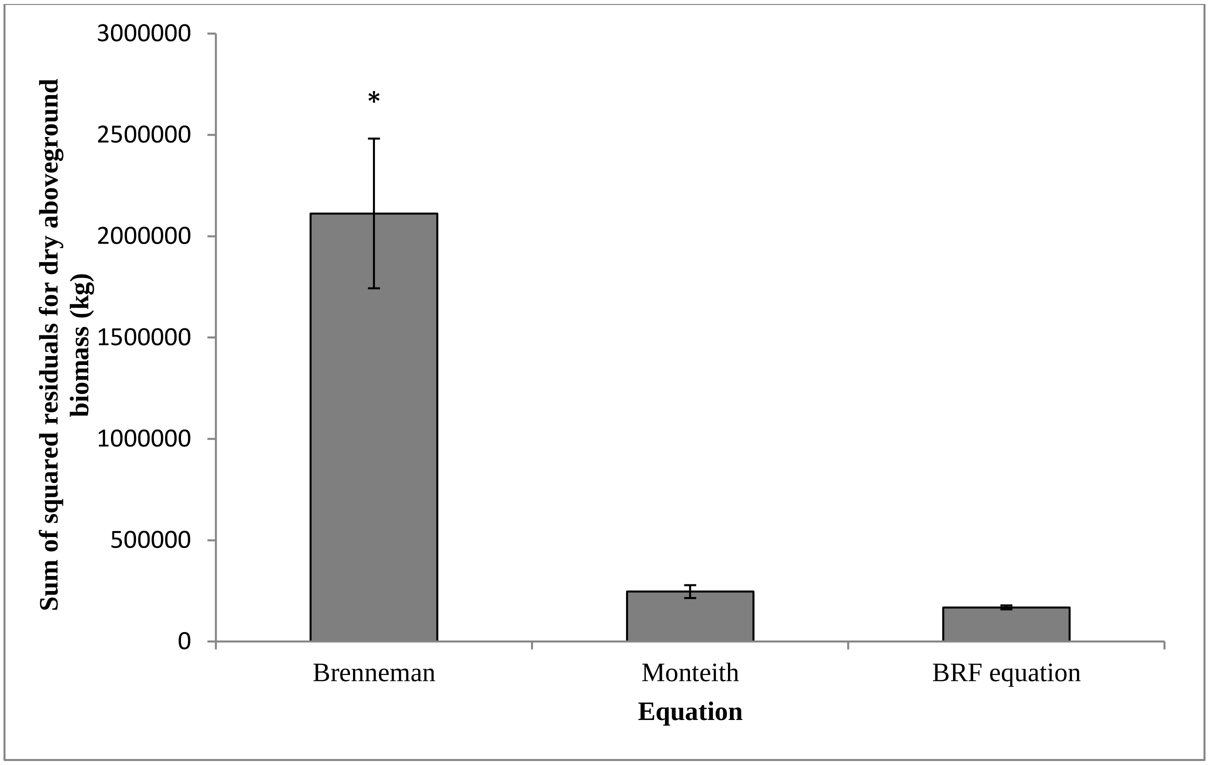


Figure 5. Plot of the sum of squared residuals for the allometric equations for *Q. prinus.* The Brenneman equation is the species-specific equation for *Q. prinus*, the Monteith equation is the general hardwood equation, and the BRF equation represents the best-fit equation given the data collected at BRF. The predicted dry weight was subtracted from the measured dry weight, squared, and summed to determine the differences between the equations and the actual data. The error bars are that standard deviation values of the squared residual values for each tree. The asterisk indicates significance.

Table 1: Paired t-test values for *Q. prinus.* This table depicts the p-values and the mean differences between the measured dry weights of *Q. prinus* and the outputs from the allometric equations.

***Q. prinus* equation**	**P-value (Two-tailed)**	**Mean difference (actual-predicted)**
Brenneman species-specific equation	0.032	-270.71
Monteith general hardwood equation	0.11	73.22
BRF equation	0.65	-18.22

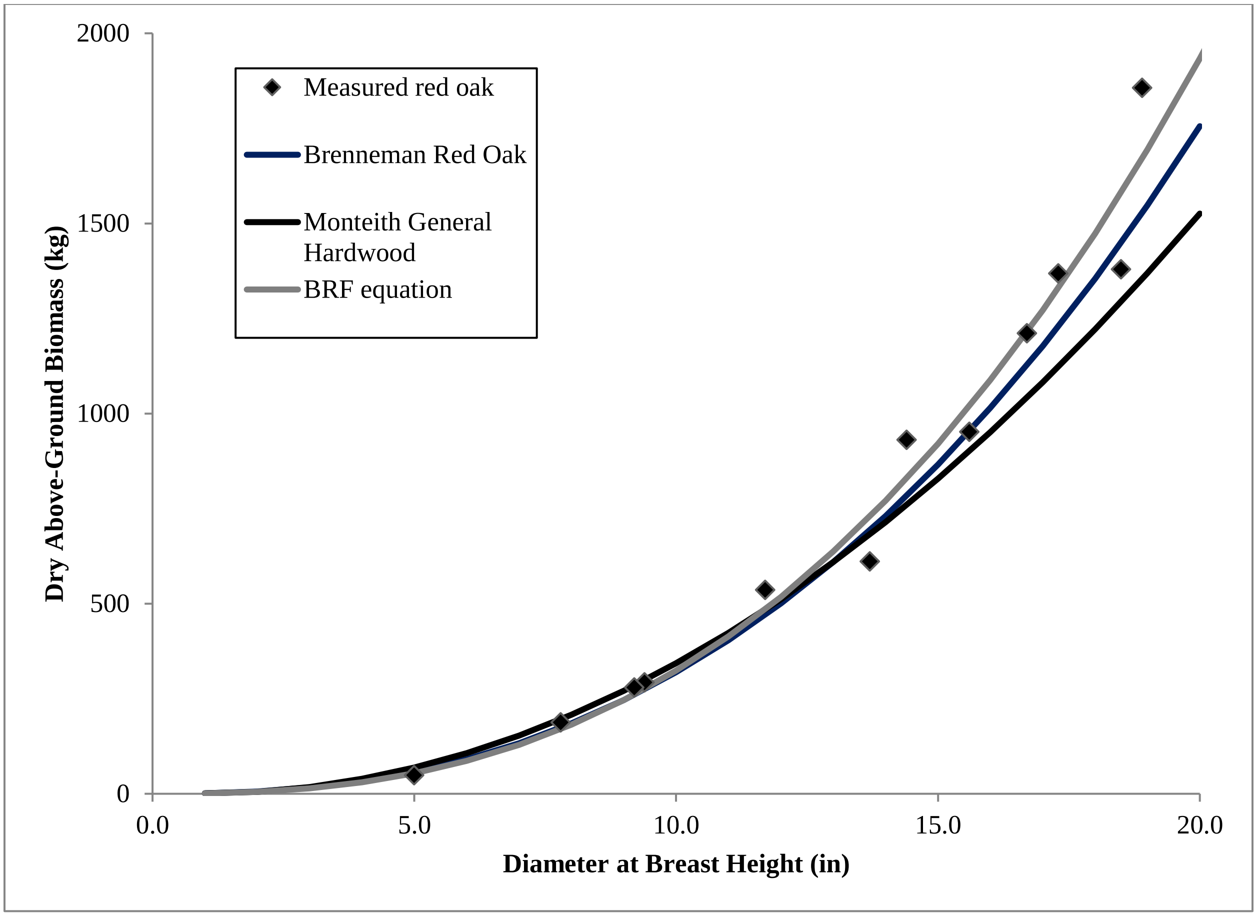
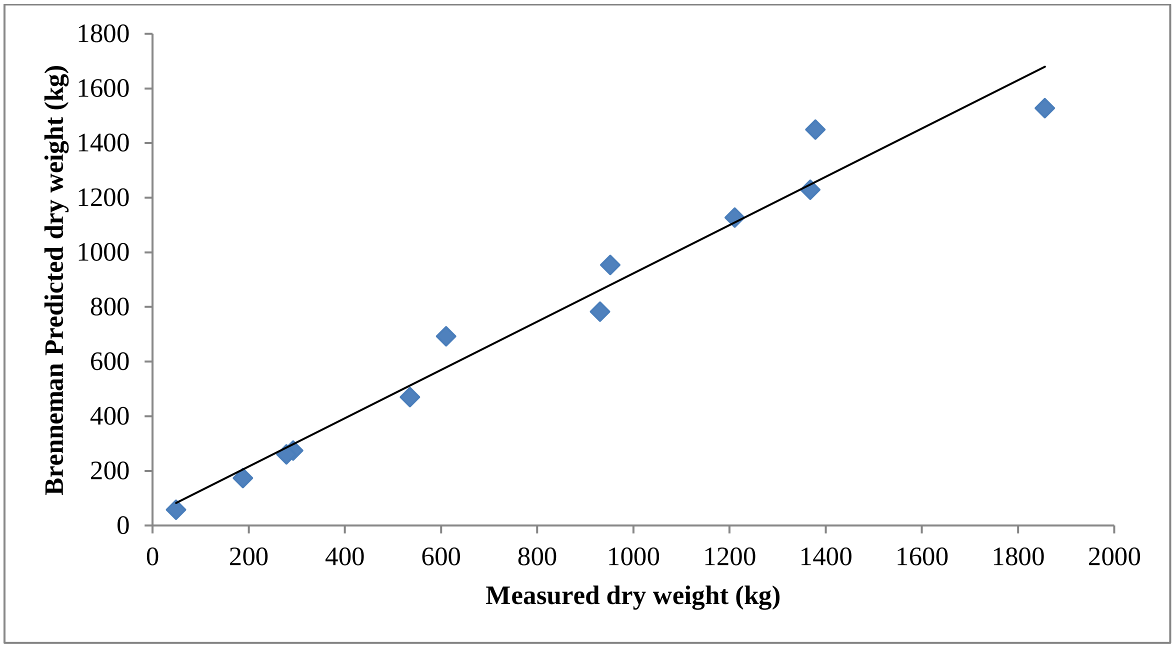


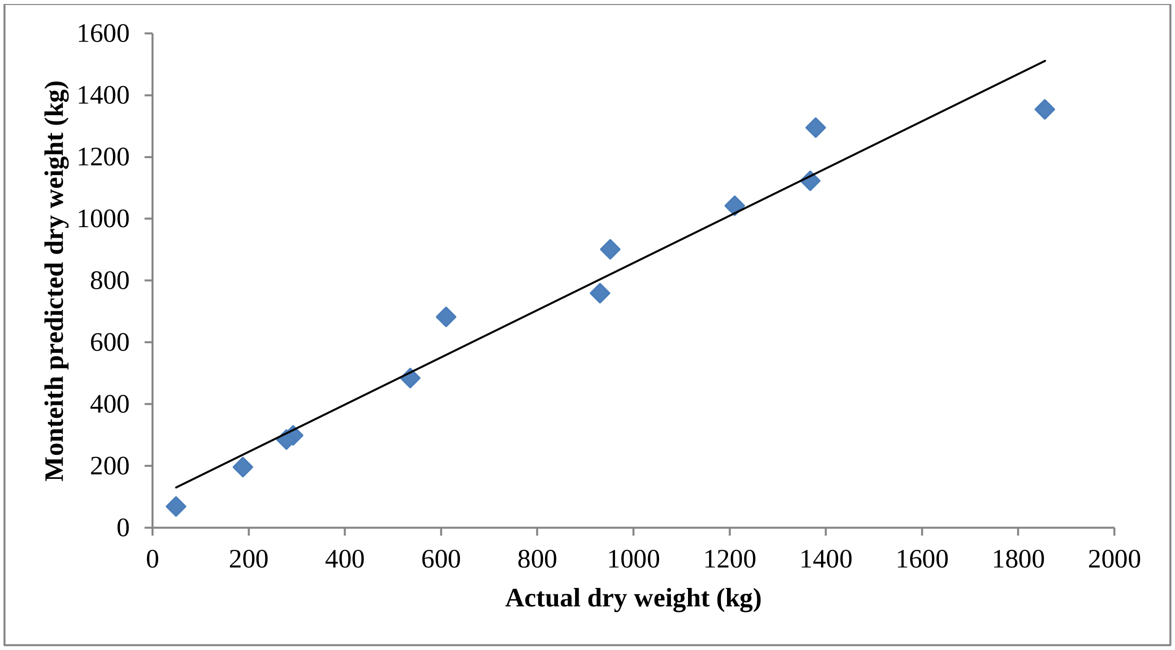
Figure 6. Plot of *Q. rubra* measured dry weight and the outputs from the allometric equations. The data points represent the data from the felled trees, diameter at breast height plotted against dry aboveground biomass. The lines represent outputs from the allometric equations at every given diameter. The Brenneman equation (Biomass= ((2.4601*(DBH)^2.4572)/2.205) and the BRF equation (Biomass=Exp(-2.5637+2.57925ln(DBH)) for *Q. rubra* differ from that of *Q. prinus*, however the Monteith equation is the same for both tree species.

a)



Brenneman Predicted dry weight (kg)
1800
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Measured dry weight (kg)

b)



Monteith predicted dry weight (kg)
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Actual dry weight (kg)

c)

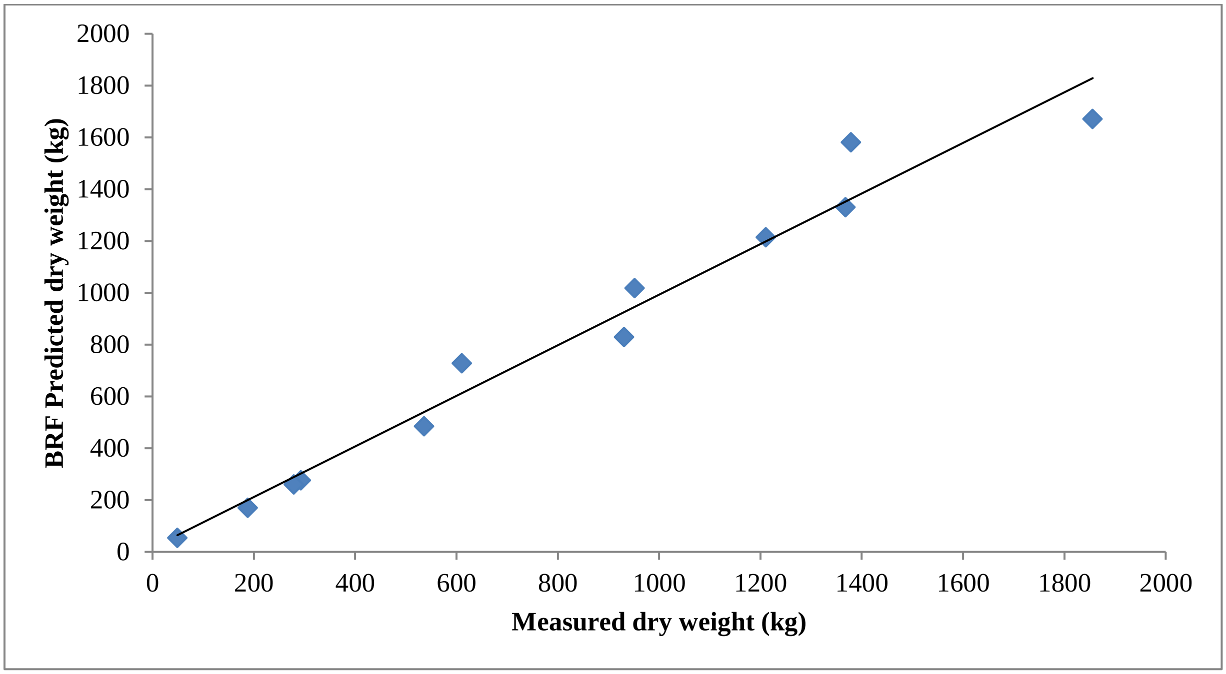


Figure 7: Correlation plots for determining best fit model for *Q. rubra.* These plots were used to calculate the R^2 in determining the best fit model for *Q. rubra*. a) *Q. rubra* species-specific equation plotted against actual dry weight (R^2=.97). b) General hardwood equation plotted against actual dry weight for *Q. rubra* (R^2=.96). c) BRF equation for *Q. rubra* plotted against actual dry weight (R^2=.97).

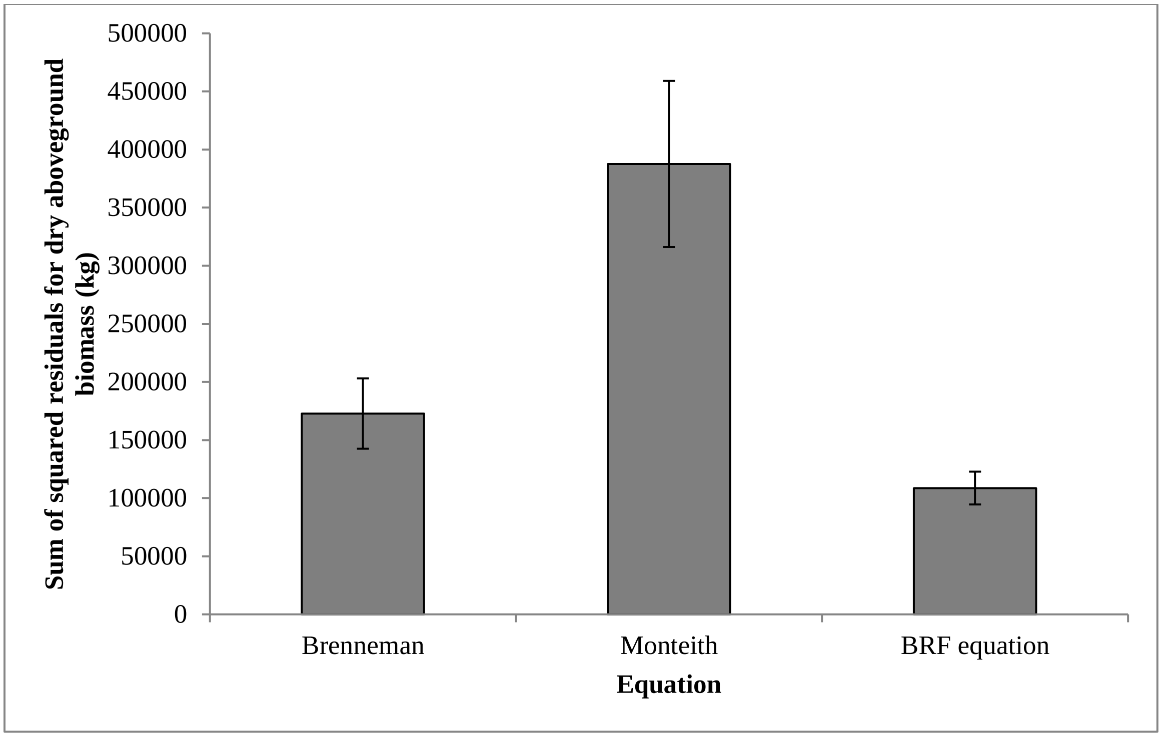


Figure 8. Plot of the sum of squared residuals for the allometric equations for *Q. rubra.* The Brenneman equation is the species-specific equation for *Q. rubra*, the Monteith equation is the general hardwood equation, and the BRF equation represents the best-fit equation given the data collected at BRF. The predicted dry weight was subtracted from the measured dry weight, squared and summed to determine the differences between the equations and the actual data. The error bars are that standard deviation values of the squared residual values for each tree.

Table 2: Paired t-test values for *Q. rubra.* This table depicts the p-values and the mean differences between the measured dry weights of *Q. prinus* and the outputs from the allometric equations.

***Q. rubra* equation**	**P-value (Two-tailed)**	**Mean difference (actual-predicted)**
Brenneman species-specific equation	0.12	54.38
Monteith general hardwood equation	0.057	96.92
BRF equation	0.93	2.54