Estimating Aboveground Biomass, Carbon Storage, and Forest Change in a Northeastern Deciduous Forest

Clara Fernandez Odell, Barnard College Department of Environmental Science





Research Mentors:
Peter Bower, Barnard College and William Schuster, Black Rock Forest
Thesis Advisor:
Elizabeth Cook, Barnard College

Final Thesis

Abstract

Atmospheric carbon has been rising over the past century, in large part due to anthropogenic carbon emissions. Temperate forests are a significant sink of carbon and accurately estimating carbon storage in these forests is an important element of managing for carbon sequestration. Aboveground dry biomass is used to approximate carbon storage in trees. The development of species- and location-specific allometric equations that estimate aboveground dry biomass in trees is an important step in estimating carbon storage. Destructive sampling at Black Rock Forest in southern New York was used to develop new allometric equations for three dominant native tree species: red oak, chestnut oak, and black birch. From these equations, aboveground dry biomass was estimated. There were statistically significant differences between estimates developed using data from Black Rock Forest and estimates generated using previously published allometric equations. The new equations were applied to data from long-term forestry plots to develop estimates for carbon sequestration in these three species from 1936-2018. As the forest matures, oak mortality increases, and black birch becomes a more significant part of the canopy, overall carbon sequestration has begun to plateau around 7.8 kg C per square meter. The results of this study suggest that the development of accurate, specific allometric equations is significant to the adequate evaluation of forest carbon stocks and that changes in species composition may alter the overall quantity and rate of carbon sequestration in temperate forests.

Table of Contents

Abstract……...……...1

Table of Contents…….……...…2

Introduction……..……3

Methods…….....……..8

Results……...…...14

Discussion……...……..21

Conclusions and Recommendations……..29

References……...……...…...31

Appendices……36

Introduction

Atmospheric carbon and forests

Concentrations of atmospheric carbon dioxide have been increasing over the past century, in large part due to anthropogenic carbon emissions (IPCC 2018). The increase of carbon dioxide in the atmosphere has been linked to changes in global climate, with potentially significant social and ecological impacts. To mitigate climate change, scientists, policy makers, and land managers are making efforts to reduce carbon emissions to the atmosphere and to sequester more carbon through artificial capture methods and natural ecosystem storage.

Temperate forests are one of the major terrestrial sinks of atmospheric carbon dioxide (Brown 2002). Estimates vary, but temperate forests constitute roughly 10% of the global terrestrial carbon pool (Ashton 2012). In temperate forests in the continental United States, approximately 35-50% of total carbon is sequestered in vegetation through photosynthesis (Dixon et al. 1994). The vast majority (>95%) of carbon stored in temperate forest vegetation is in live trees. Other major carbon pools in temperate forests include soil, dead and decomposing wood, and forest floor debris (Bradford et al. 2010). The carbon stored in live trees is split between aboveground biomass and roots. Most of the tree's biomass (between 60-90% depending on species, location, condition, and other factors) is aboveground in the tree's leaves, branches, and trunk (Nabuurs et al. 2007).

Estimating the quantity of carbon stored in living trees helps us understand temperate forests as a carbon reservoir. Establishing the size of the carbon pool and the carbon flux from the atmosphere to biomass allows us to make recommendations for selective deforestation and felling, afforestation, and other forest management strategies that could potentially mitigate the

impacts of increasing atmospheric carbon. Forest land use can create a substantial carbon flux; deforestation, for instance, can be a significant source of carbon to the atmosphere while careful management of old-growth and secondary forests can create a significant sink. Because of the size and global distribution of these fluxes, the impact of managing forests for carbon sequestration is important for climate change mitigation.

Allometric equations and estimating carbon storage

Allometric equations are a key tool used to estimate the quantity of carbon stored in a tree's biomass. These equations are models that use parameters such as diameter at breast height (DBH), which are non-destructive, to estimate values that require more labor and disturbance to sample, such as aboveground dry biomass. Destructive sampling—the felling, drying, and weighing of live trees—is used to determine the relationship between DBH and dry biomass. Several formats of allometric models relating DBH to aboveground dry biomass exist (Table 1). Brenneman et al. (1978) employs an exponential equation while Jenkins et al. (2003) uses a natural log function to describe the relationship between biomass and DBH.

Table 1. Existing allometric equation formats and parameters from prior literature (Brenneman et al. 1978, Jenkins et al. 2003) currently in use for aboveground biomass estimation of chestnut oak, red oak, and black birch at Black Rock Forest. *B0* and *β1* refer to equation parameters.

Author, Tree Species/Type	**Equation**
Brenneman et al. 1978 general	$Biomass=\beta 0(DBH)^{\beta 1}$
Chestnut oak (*Q. prinus*)	$Biomass=1.55(DBH)^{2.73}$
Red oak (*Q. rubra*)	$Biomass=2.46(DBH)^{2.45}$
Black birch (*B. lenta*)	$Biomass=1.65(DBH)^{2.66}$
Jenkins et al. 2003 general	$Biomass=Exp(\beta 0+\beta 1 \ln DBH)$
Hard maple/oak	$Biomass=Exp(-2.01+2.43 \ln DBH)$
Soft maple/birch	$Biomass=Exp(-1.91+2.36 \ln DBH)$

It is important that allometric equations are specific to both the tree species and the location where estimates are desired (Fatemi et al. 2011). Allometric equations that generalize in terms of species (such as the Jenkins et al. 2003) or region (such as most national-scale estimators) risk mis-estimating aboveground dry biomass, leading to over- or underestimations of carbon pools in forests (Wutzler et al. 2011).

Since the development of allometric equations involves felling and weighing live trees, it is not practical to develop specific equations for all regions or species. However, a species- and location-specific allometric equation gives a much clearer picture of how much carbon is sequestered in the ecosystem and how shifts in forest extent and species composition might alter the carbon pool and flux (Jenkins et al. 2003). Where the quantity of trees is sufficient and the risk of serious disturbance to the forest ecosystem from destructive sampling is low, specific allometric equations are an important step in developing an accurate carbon storage estimate.

Developing allometric equations at Black Rock Forest

This study on forest carbon estimates and the development of allometric equations was conducted at Black Rock Forest (BRF). BRF is a private forest reserve managed by the Black Rock Forest Consortium, a group that includes several academic and research institutions in the New York City metro area. BRF is located in the Hudson Highlands region of New York State, on the western edge of the Hudson River (Figure 1). Most of the forest within the preserve is secondary growth, between 100 and 150 years old. Several reservoirs and streams, one natural lake, and multiple former homestead sites are also located within the forest.

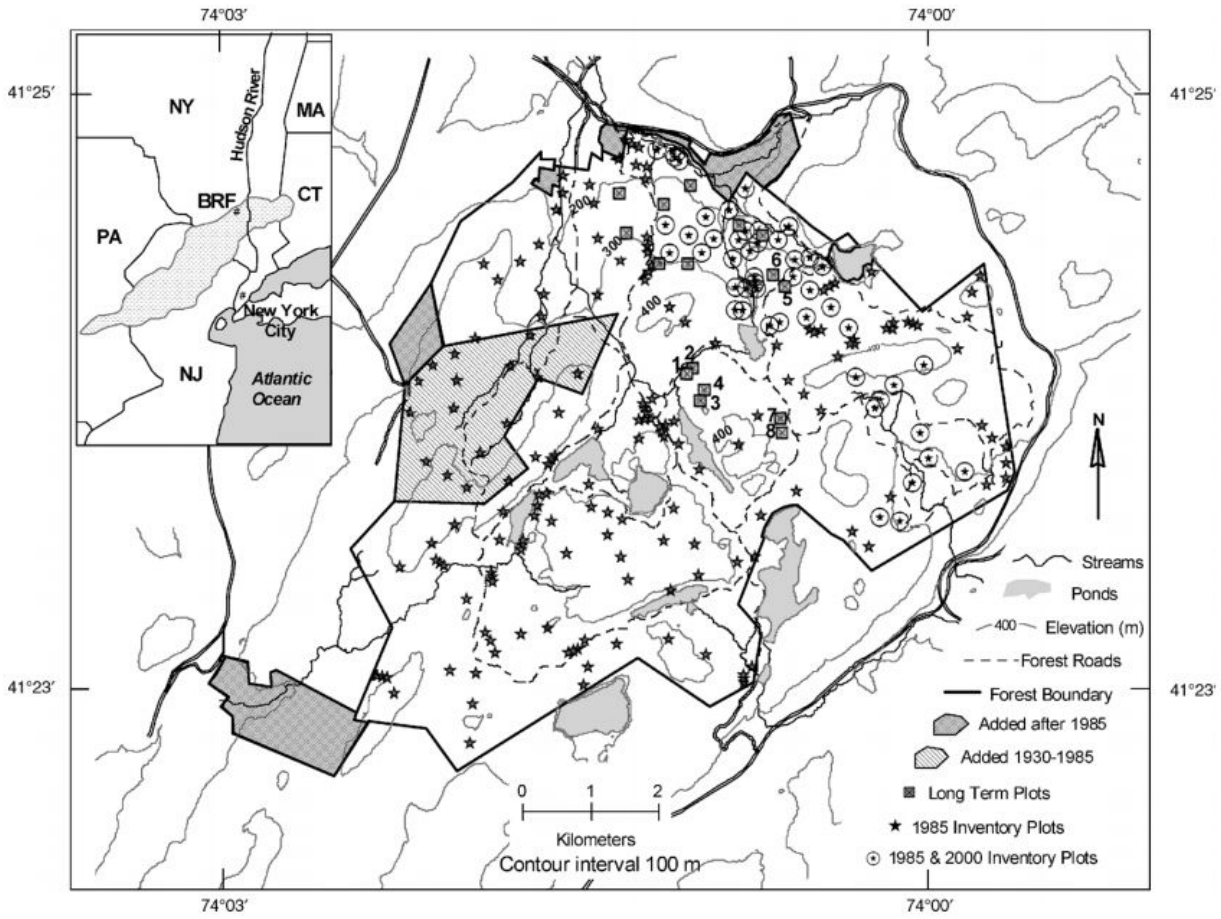

Figure 1. Map of Black Rock Forest showing the location of the long-term plots (squares), forest inventory plots (stars and circles), and the forest in the context of southern New York (inset). From Schuster et al. (2008).

Developing an accurate evaluation of carbon stocks in Black Rock Forest has been a goal of the Consortium for several decades (Schuster 2012). BRF contains eight long-term forestry plots that have been monitored on a regular basis since 1931 (Figure 2). These plots were intended to track the succession of a (at the time) young forest. As more has been learned about the critical role that forests play in carbon sequestration, the plots have also been used to estimate the quantity of carbon stored at BRF and the size of the flux between BRF trees and the atmosphere (Schuster 2012).

The allometric equations that have been used in the past to estimate carbon storage at BRF are from different ecological regions with different climate, soil, and disturbance conditions than BRF. These equations include those generated from sampling by Brenneman et al. (1978) in West Virginia and the national-scale estimators provided in Jenkins et al. (2003). Because these equations were developed from destructive sampling completed in other regions, trees of the same species grown at BRF may have differing growth rates and forms, aboveground dry biomass proportions, and quantities of carbon storage. These potential differences mean that the development of specific allometric equations for BRF could alter the current estimates for carbon storage in the forest.

Forest changes at Black Rock Forest

The majority of the forest at BRF is secondary and has progressed from clear-cut to relatively mature over the past 100 to 150 years. When BRF's long-term plots were established, most trees were immature and no distinct canopy was present. Now, there are several mature trees on each plot and distinct canopy and understory layers exist (Schuster 2012). Over this span of time carbon has accumulated in biomass, detritus, and soil and the overall size of the carbon pool in BRF's long-term plots has increased significantly (Schuster et al. 2008).

The forest has also seen shifting climatic conditions and ecological dynamics that have altered the species composition of the forest. BRF was historically an oak-chestnut forest, with hickory and maple rising in dominance after severe chestnut mortality (Schuster 2012). Red oak is by far the most common mature tree, comprising about 70% of the canopy (Schuster et al. 2008). Since the 1990s, however, black birch has become especially widespread in forest gaps, regions of tree mortality, and areas where oak seedling recruitment has been low

(Falxa-Raymond et al. 2012). If current trends continue, black birch may be the dominant or co-dominant species in BRF's canopy within the next half-century (Schuster et al. 2008).

One potential application of generating new species-specific, location-specific allometric equations at BRF would be to understand how these changes in the forest's species composition might affect the amount of carbon sequestered in the forest. Some models suggest that when deciduous forests transition from oak-dominant to birch-dominant, they no longer sequester or retain carbon as effectively (Falxa-Raymond et al. 2012). BRF's long-term plots, which are representative of the species composition of the forest as a whole, are a useful site to examine if carbon dynamics change in response to species shift at BRF.

This study aims to determine how and to what extent species- and location-specific allometric equations at Black Rock Forest differ significantly from generalized allometric equations for red oak, chestnut oak, and black birch. I will use equations generated at Black Rock Forest to develop new estimates for carbon storage in the forest's long-term plots. With these estimates, I will investigate how the use of species- and location-specific allometric equations changes our understanding of how forest species shift affects carbon sequestration at Black Rock Forest.

Methods

Tree selection

Generating allometric equations requires destructive sampling. For allometric equations that relate diameter at breast height or another growth metric to aboveground dry biomass, destructive sampling involves felling trees across a range of size classes, weighing the full tree,

drying a subsample to calculate the wet-to-dry biomass ratio, and applying this ratio to the entire measured mass of the tree.

For this study, the first two selective criteria for trees targeted for destructive sampling were species and location. This study focuses on developing allometric equations from sample individuals of three species: chestnut oak, red oak, and black birch. All sample trees were felled within the boundaries of Black Rock Forest (see Figure 1 in Introduction) between 2000 and 2019. Within the bounds of the forest, areas used for other studies or within the long-term plots were not sampled to avoid disturbing ongoing research. Most trees were felled near roadways, for ease of felling, weighing, and transportation of cut wood. However, trees directly overhanging roadways were avoided because of the more open canopy near roads and because vehicle activity can have an adverse impact on root growth. Most sampled trees grew in closed or near-closed canopies. Trees in meadows, open fields, or adjacent to bodies of water were avoided because of the potential for higher light availability to alter growth patterns and biomass accumulation.

An effort was made to sample from a range of size classes within each species. Sapling and immature trees (DBH<5 cm) were included in the destructive sampling process for black birch, although they were excluded from sampling of red oak and chestnut oak due to a lack of viable oak saplings and young trees. A particular effort was made to obtain a large sample size of trees at larger diameters (DBH>35 cm), as these trees store the bulk of carbon in live wood. Additionally, biomass estimates for trees of large diameter tend to differ most widely between allometric equations.

Trees with significant abnormalities that would affect aboveground dry biomass were excluded from sampling. Significant abnormalities include large broken limbs, highly unusual growth forms, and decay or fungus around the base. Coppiced trees (those with two or more main trunks) were also excluded from the study, as they are not representative of the growth pattern of the majority of the trees at BRF.

In total, 11 red oak, 12 chestnut oak, and 21 black birch were sampled between 2000 and 2019. All trees were sampled during the mid to late growing season (July-October).

Felling and weighing

Immediately prior to felling, the species of the tree was confirmed and the diameter at breast height was taken by at least two participants. The diameter was recorded at 4.5 feet above ground height. The mean of these diameters became the official recorded diameter of the sample tree.

Each sample tree was felled using a chainsaw, with the point of felling as close to the base as possible. Immediately after felling, trees were cut into pieces weighing under 60 kg. The height and two or more stump diameters were taken in order to estimate stump mass. All aboveground sections of the tree (trunk, large branches, fine branches) were weighed using a hanging scale. Masses were recorded immediately. During weighing, leaves were not removed from the branches; however, no effort was made to recover leaves that fell off during the felling and weighing process.

A section of the trunk near the base (<10 cm thick) was cut and immediately wrapped in plastic to prevent desiccation. This section was used as the drying sample to determine the ratio

of wet-to-dry biomass. The purpose of calculating the ratio between wet-to-dry biomass is to exclude tree moisture content, which is seasonally and climatically variable, from the study.

Drying and calculating aboveground dry biomass

The drying subsample was cut into four equal sections, each section weighing less than 4000.00 g. Upon removal of the wrapping plastic, each section was immediately weighed on a balance to the nearest 0.00 g. The sections were laid out to dry inside at a temperature of 23 °C.

Each section was weighed daily at the same time until the weight remained constant for at least three measurements, indicating that all remaining water in the wood had evaporated. The ratio between the final dry mass and the initial wet mass was calculated for each section. The mean of this ratio across all four sections was considered the official drying factor of the tree. The volume and final dry mass of the pucks was also used to calculate stump mass from stump volume measurements taken in the field.

The total wet biomass of the tree from field measurements was multiplied by the drying ratio of the tree to give the total aboveground dry biomass. This is considered the official mass of the tree for the purposes of generating the allometric equations.

Developing allometric equations

Allometric equations for each species were generated from DBH and aboveground dry biomass data. The format of the equation is Biomass=Exp($\beta 0$+$\beta 1$lnDBH), as proposed by Jenkins et al. (2003). $\beta 0$ and $\beta 1$ are the equation parameters that determine the fit of the allometric curve. The Jenkins et al. (2003) model was selected over the Brenneman (1978) model because of its widespread use in federal forest management and because it is easier to fit to new data points using Excel's Solver package.

Two different allometric equations were used to generate the previous predicted biomass for each study species. The equations for chestnut oak and red oak were based on the Jenkins et al. (2003) hard maple and oak equation while the equation for black birch was based on the Jenkins et al. (2003) soft maple and birch equation (Table 1).

Excel's Solver was used to minimize the residual between predicted biomass (using the Jenkins et al. equation) and actual biomass of the sampled trees. The $\beta 0$ and $\beta 1$ parameters that minimized the residuals between the observed biomass and the equation's calculated biomass became the new parameters for the BRF-specific allometric equation for each species.

Comparing BRF equations with equations in prior literature

To determine how the generation of BRF-specific allometric equations affects aboveground dry biomass estimates, the new equations were compared with equations from prior literature that have been previously used to estimate biomass and carbon sequestration at Black Rock Forest. These equations and model parameters come from Brenneman et al. (1978) and Jenkins (2003). Brennemen et al. (1978) equations were developed from destructive sampling conducted in West Virginia and Jenkins et al. (2003) were compiled from a nationwide literature search. The observed biomass of each study tree, the biomass predicted by the new BRF equation, and the biomass predicted by equations from Brenneman et al. (1978) and Jenkins et al. (2003) were compared.

To compare the fit of each equation, observed biomass from each sample tree was plotted against the calculated biomass for that tree's diameter. Linear regression was used to generate an R^2 value indicating the fit of each equation for the observed biomass of each species, resulting in a total of nine linear regressions.

One way ANOVA with a post-hoc Tukey HSD test was used to further test the statistical significance of differences between the biomass values predicted by each equation. The predicted biomass values for each equation were split into groups of DBH >35 cm and DBH <35 cm so that each set of equations was compared across the same size class.

long-term plots at BRF and estimating carbon storage

There are eight long-term forestry plots at BRF where DBH, tree growth, recruitment, and mortality, tree condition, and species composition have been recorded regularly (initially every five years, now annually) since 1931. These plots lie on a range of soil types, slopes, and aspects. The maturity, density, and species composition of BRF as a whole is accurately reflected in these plots according to randomized forest inventories conducted in 1985 and 2005 (Schuster et al. 2008).

Since DBH and species have been so consistently recorded for 90 years, allometric equations that use DBH as a parameter were applied to estimate aboveground dry biomass for the three study species in these plots. Although the application of these allometric equations to the study species does not give a total aboveground dry biomass estimate (as there are trees of other species in the plots) it does allow the estimation of how much biomass is allocated to each of these three species in the plots, and how the allocation of biomass has changed over time.

To calculate carbon storage from aboveground dry biomass estimates, a known ratio of carbon to total dry weight was applied. For both species of oak, this ratio is 0.495:1 and for birch this ratio is 0.485:1 (Wutzler et al. 2011). As birch wood is slightly less carbon-dense than oak wood, a birch will sequester slightly less carbon than a red oak or chestnut oak with the same

total aboveground dry biomass. However, given error in other parts of the sampling process such as the calculation of drying factor, this distinction is likely fairly insignificant.

An estimate of carbon storage per area was developed by summing the total carbon storage estimate for each year across all eight plots and dividing by the total area of all plots (5139 m^2).

Results

Destructive sampling at Black Rock Forest

Between 2000 and 2019, a total of 44 trees across all three study species were felled and weighed (for full felling and weighing data see Appendix A). Of all three study species, only black birch included samples of trees with DBH<10 cm, and the black birch dataset has the highest proportion of trees with DBH<20 cm. This difference in size class distribution was partially due to inherent interspecific differences—black birch is generally smaller than oak—and partially due to a lack of sapling and juvenile oak trees at BRF.

Allometric equations generated using Black Rock Forest samples

The destructive sampling described above resulted in three allometric equations, one for each study species. Allometric equations were generated using the $Biomass=Exp(\beta 0+\beta 1 \ln DBH)$ employed by Jenkins et al. (2003) which relate diameter with aboveground dry biomass.

The generated equations predicted a positive exponential relationship between diameter at breast height and aboveground dry biomass for each species. The R^2 value relating DBH and aboveground dry biomass for each dataset was greater than 0.85 (Figure 2).

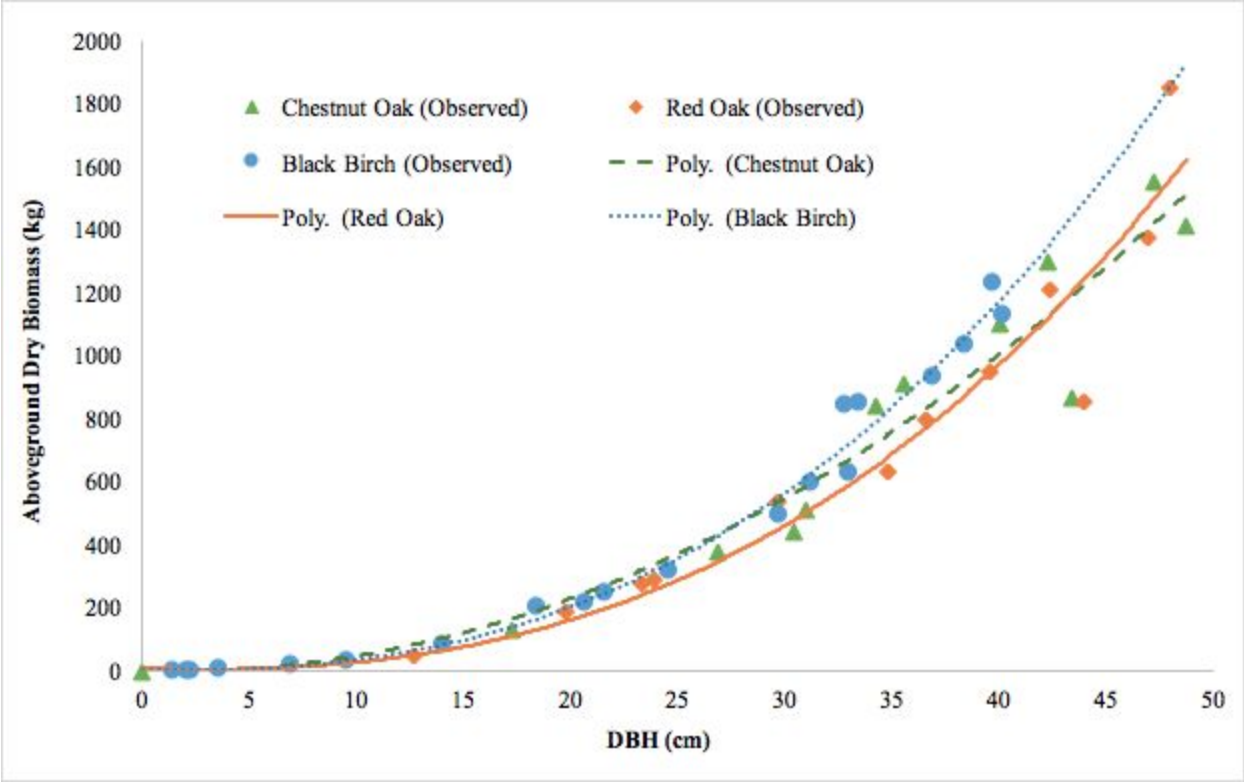

Figure 2. Diameter at breast height and measured aboveground dry biomass for chestnut oak, red oak, and black birch with curves showing predicted dry biomass by DBH based on BRF-generated equation.

Comparison of BRF equations to previous literature

For all three species, each new BRF equation had a smaller sum of squared differences (relative to observed biomass) than equations the taken from Brenneman et al. (1978) and Jenkins et al. (2003) that were previously used to estimate aboveground dry biomass and carbon storage at BRF (Table 2).

Table 2. Parameters and R^2 values of BRF-generated equations and literature equations for chestnut oak, red oak, and black birch. For BRF and Jenkins et al., Biomass=Exp($\beta 0+\beta 1$lnDBH). For Brenneman et al., Biomass=$\beta 0(DBH)^{\beta 1}$.

Species / Equation	$\beta 0$	$\beta 1$	R^2
Chestnut Oak			
Black Rock Forest	-0.8379	2.0999	0.891
Jenkins et al. (2003)	-2.01	2.43	0.884
Brenneman et al. (1978)	1.55	2.73	0.875
Red oak			
Black Rock Forest	-2.2763	2.5323	0.917
Jenkins et al. (2003)	-2.01	2.43	0.915
Brenneman et al. (1978)	2.46	2.45	0.915
Black birch			
Black Rock Forest	-2.6859	2.5927	0.984
Jenkins et al. (2003)	-1.91	2.36	0.983
Brenneman et al (1978)	1.65	2.66	0.983

Linear regressions plotting observed biomass against calculated biomass for each species using each of the three equations generated R^2 values that indicate the strength of the relationship between each equation and actual biomass at BRF. All equations had R^2 values greater than 0.85 for all species. For each species, the BRF equation had the highest R^2 value, but differences in linear regression and R^2 were not significant. For full linear regressions, see Appendix B.

There was some variation between equations for trees in the larger size class (>35 cm DBH). For chestnut oaks over 35 cm, Brennemen et al. (1978) and Jenkins et al. (2003) both overpredicted biomass relative to observed and BRF-predicted values (Figure 3). Jenkins et al.

(2003) underpredicted biomass for black birch over 35 cm (Figure 5). Neither equation varied for red oak at any size class (Figure 4). For trees with DBH less than 35 cm, equations varied less and fewer clear distinctions were seen between BRF-specific equations and the Brenneman et al. (1978) and Jenkins et al. (2003) equations (Figures 3-5).

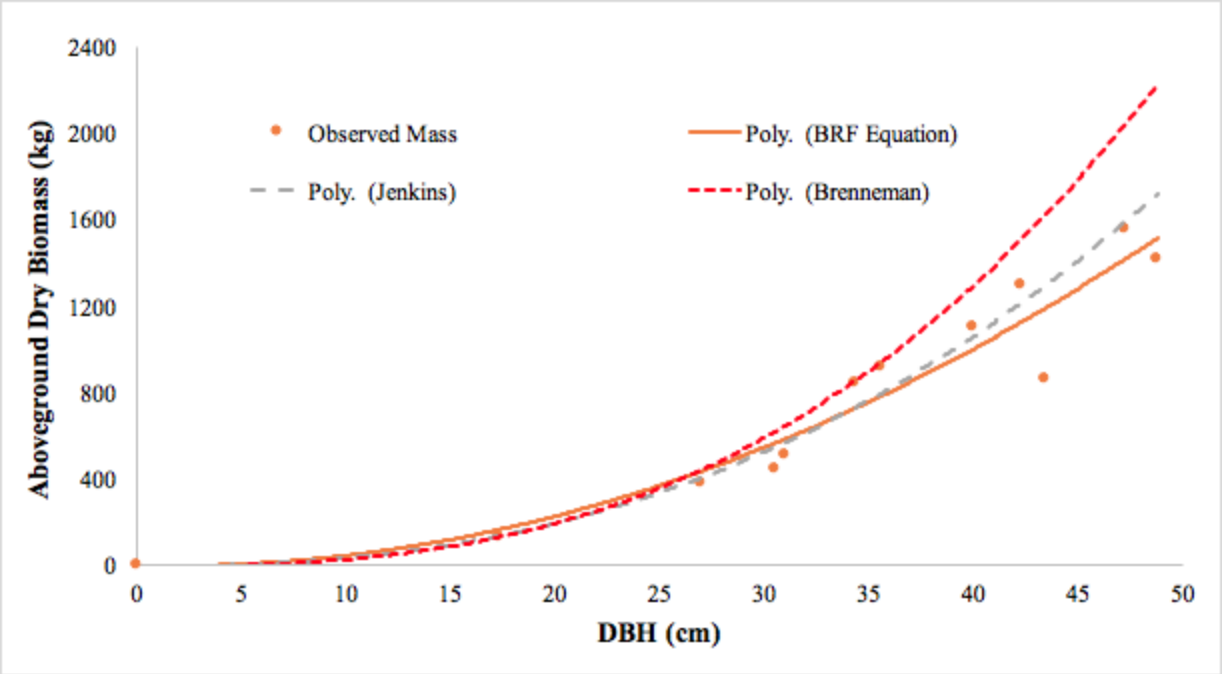

Figure 3. Aboveground dry biomass for chestnut oak (*Q. prinus*) observed from sampling (orange points), predicted from BRF equation (orange curve), predicted from Jenkins et al. (grey curve), and predicted from Brenneman et al. (yellow curve).

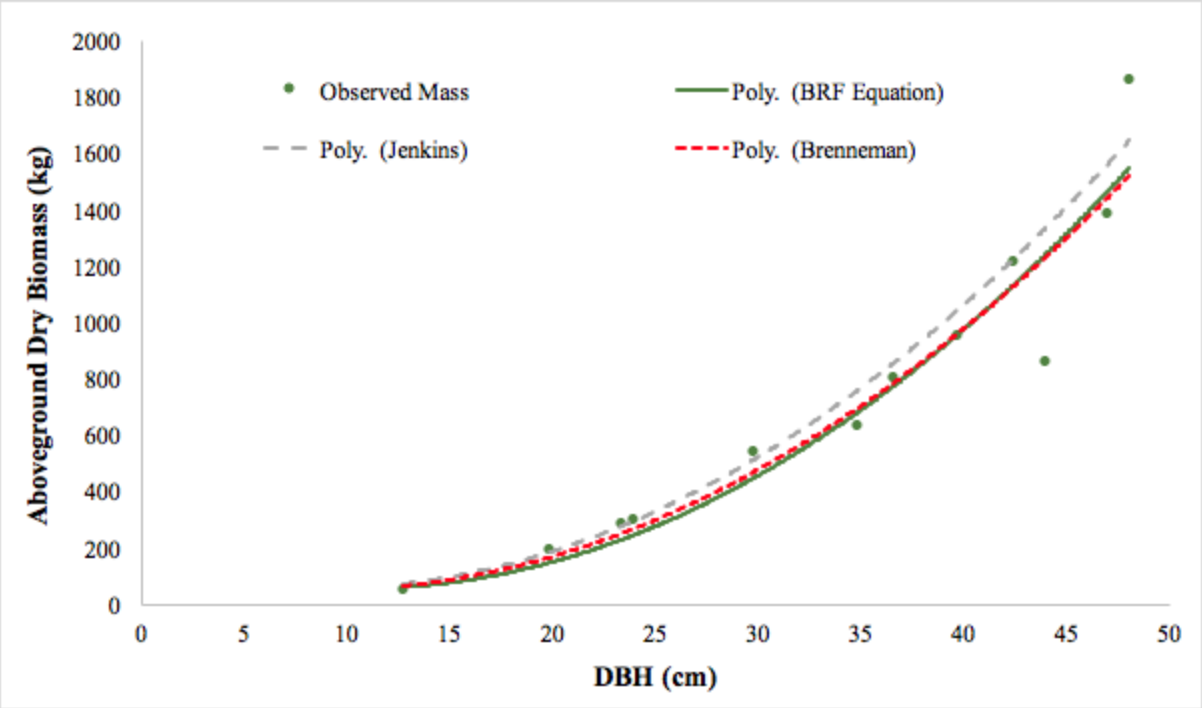

Figure 4. Aboveground dry biomass for red oak (*Q. rubra*) observed from sampling (green points), predicted from BRF equation (green curve), predicted from Jenkins et al. (grey curve), and predicted from Brenneman et al. (red curve).

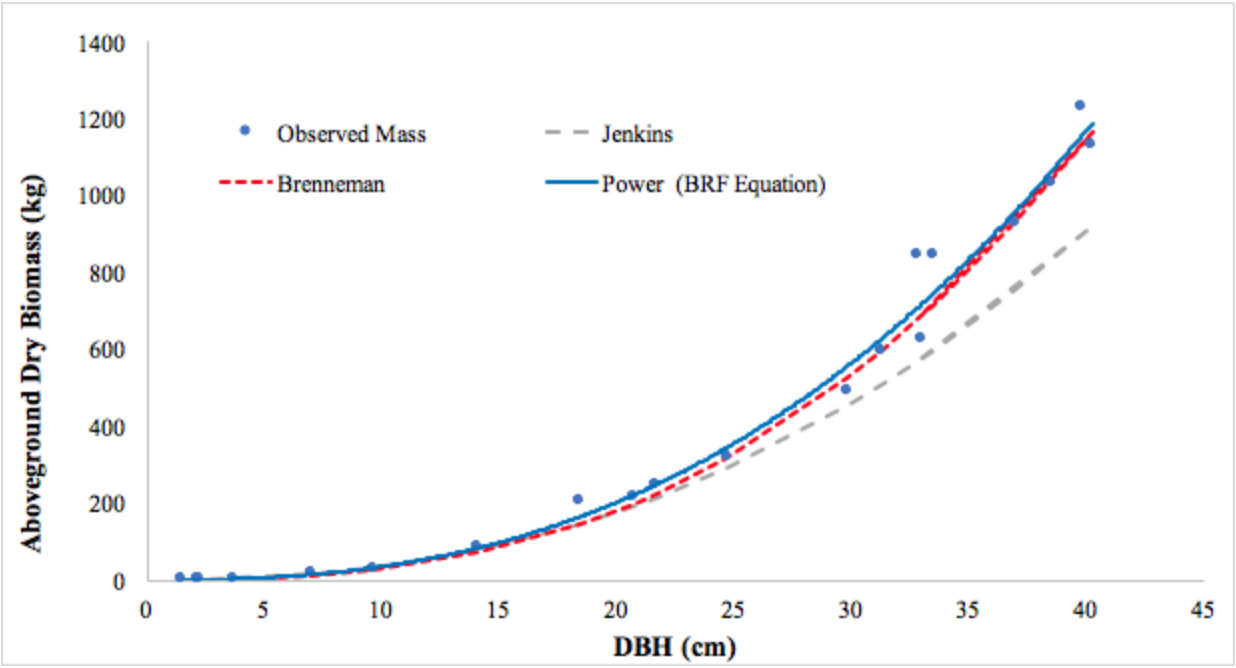

Figure 5. Aboveground dry biomass for black birch (*B. lenta*) observed from sampling (blue points), predicted from BRF equation (blue curve), predicted from Jenkins et al. (grey curve), and predicted from Brenneman et al. (red curve).

ANOVA showed statistically significant differences in predicted biomass between the BRF equation and Brenneman et al. (1978) for chestnut oak with DBH greater than 35 cm ($p<0.05$, $n=7$). There was also a statistically significant difference between Jenkins et al. (2003) and both the BRF equation and Brenneman et al. (1978) for black birch with DBH greater than 35 cm ($p<0.05$, $n=5$). ANOVA was also conducted for each equation for black birch with DBH greater than 30 cm to increase the sample size, differences between the equations were minimally significant ($p=0.17$, $n=8$). There were no significant differences between equations for trees in the smaller size class or for red oaks of any size. For full ANOVA results, see Appendix C.

Carbon sequestration at Black Rock Forest

The amount of carbon stored both in each study species and across the long-term plots at Black Rock Forest has generally increased since 1936. The period of most rapid increase was from 1936 to 1965, followed by a slower increase in overall carbon sequestration and eventually a plateau.

In 1936, chestnut oak sequestered the most carbon of the three study species. However, the quantity of carbon stored in chestnut oak began to decline around 1961 while the amount of carbon stored in red oak continued to increase until the early 2010s. Black birch has stored less carbon than either oak species since 1936, but the amount of carbon in birch biomass has been steadily increasing over the entire frame of data collection (Figure 6).

In 1936, the three study species combined stored slightly less than 3 kg of carbon per square meter in aboveground dry biomass. Note that this does not represent all carbon stored in aboveground dry biomass on these plots, which include several trees of species not represented

in this study. Sequestration peaked in 1998 with approximately 7.8 kg of carbon per square meter stored in aboveground dry biomass. After a slight decline in total carbon storage in the early 2000s, the total quantity of carbon stored across all three study species in the long-term plots is again just below 8 kg per square meter (Figure 6).

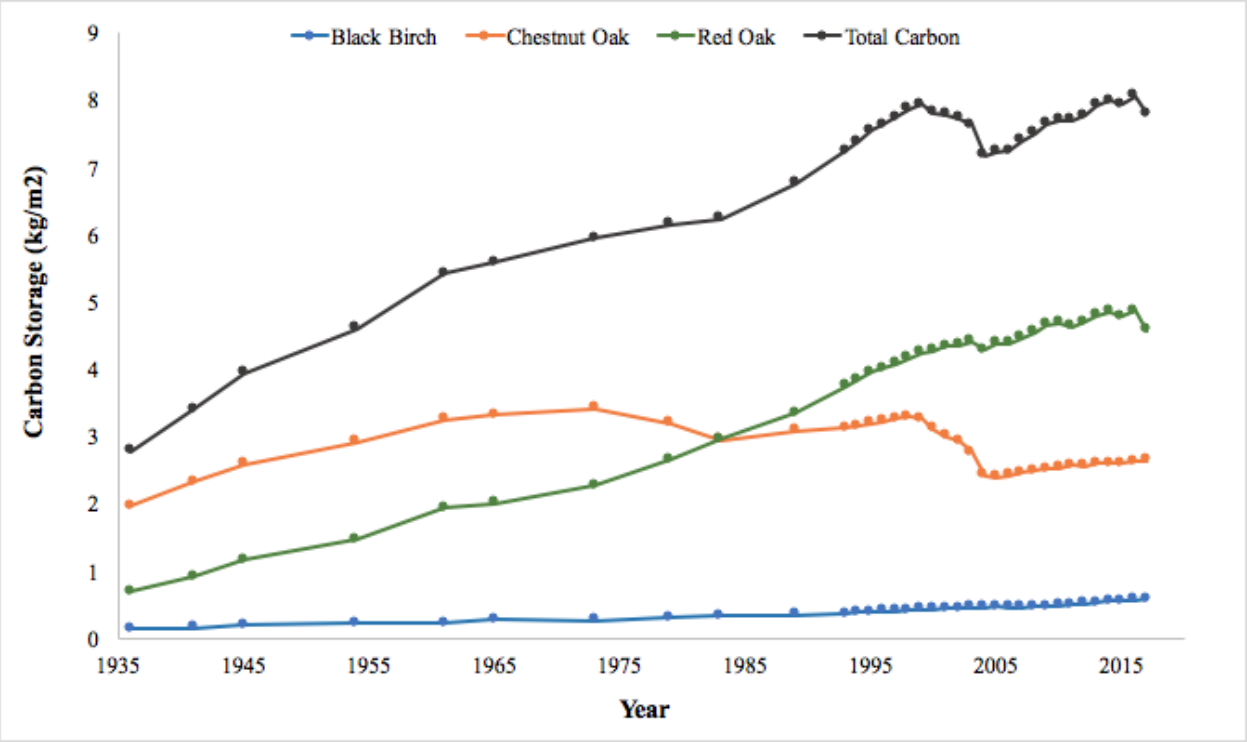

Figure 6. Carbon storage (kg per square meter) in aboveground dry biomass in each of the three study species on BRF long-term plots between 1935 and 2018, estimated using BRF equations.

Discussion

Atmospheric carbon and Black Rock Forest

Atmospheric carbon dioxide has been increasing over the past century and is a significant driver of anthropogenic climate change. Managing temperate forests such as Black Rock Forest for carbon retention and increased sequestration is a tool that could mitigate some impacts of climate change. Black Rock Forest is an interesting study location because it is typical of the deciduous, oak-dominant secondary forests that make up much of the eastern United States

(Schuster et al. 2008). The first part of carbon management at Black Rock Forest—and in other similar temperate forests—is accurately measuring the size and nature of carbon reservoirs and fluxes and understanding how changes in the ecosystem will affect carbon movement and storage.

One of the primary aims of this study is to determine how much carbon is sequestered in three key species at Black Rock Forest, and what impact forest carbon sequestration at BRF may have on atmospheric carbon. By applying accurate allometric equations to long-term forestry data, we can obtain a clearer picture of whether aboveground biomass at BRF is a true carbon sink. We can also evaluate how changes in species composition may affect carbon sequestration in the present and future.

A potential application of this study is to generate recommendations for forest management that focus specifically on carbon sequestration. Managing the forest for carbon storage and climate change mitigation is one of the aims of forest managers at BRF (Schuster 2012). The evaluation of carbon storage in oak and birch could generate strategies that forest managers at BRF and elsewhere could use to improve carbon sequestration and atmospheric carbon mitigation on their forested land.

Long-term plots and aboveground carbon sequestration trends

Overall, aboveground carbon sequestration in the study species on the long-term plots at BRF has increased over the past 90 years, from about 2.8 kg of carbon per square meter across all three study species to approximately 7.8 kg of carbon per square meter. Over the past 20 years there has been a plateau around 7.6 kg of carbon per square meter across all plots.

This pattern of carbon sequestration is typical of northeastern deciduous forests. Biomass and net primary productivity studies done at Hubbard Brook Experimental Forest in New Hampshire outline three key stages of biomass and carbon accumulation in secondary successional forests: aggradation, where biomass increases steeply as trees mature; transition, where biomass wavers and can sometimes decline as mortality overtakes seedling recruitment; and steady-state, where the mature forest fluctuates around a biomass set point (Bormann and Likens 1979).

The fluctuations around the 7.8 kg per square meter plateau and the slight decline in the early 2000s indicate that Black Rock Forest is entering the transition state of carbon sequestration. The amount of carbon sequestered in the long-term plots will likely continue to see-saw and possibly decline until the steady-state of the mature forest is reached. Based on estimates from the Hubbard Brook study, transition usually begins after around 100 years of succession (Fahey et al. 2005). Most forest stands in BRF are currently 90-100 years into succession post-clearcutting. Steady-state can be reached after anywhere between 300-500 years of succession (Fahey et al. 2005). These timelines are an approximation; because BRF differs from Hubbard Brook in latitude, climate, species composition, and soil type, the actual successional age where steady-state is reached may differ widely.

Forest carbon pools at BRF

Aboveground biomass and carbon sequestration in live trees are only a part of the overall carbon sequestration picture at Black Rock Forest. Coarse and fine roots store a smaller proportion of biomass carbon than the trunk and limbs, but still contribute significantly to the overall carbon pool. In mature northeastern hardwood forests, the ratio of belowground biomass

carbon to aboveground biomass carbon is approximately 0.25 (Fahey et al. 1988). This means that an additional 25% could be added to carbon estimates at BRF in order to roughly approximate the total amount of carbon stored in live biomass in the study species on the long-term plots. With this addition, the long-term plots at BRF store approximately 9.75 kg C per square meter in live biomass in the study species. This value excludes the component ratios of individual species and differences in the proportion of carbon in aboveground tissue as opposed to root tissue, but provides a sound broad estimate.

A substantial amount of carbon is also sequestered in forest soils. Currently, there is ongoing research about the quantity of soil carbon on the long-term plots at BRF. Generally, pools of soil carbon and rates of soil carbon sequestration in temperate forests are considered stable and relatively insensitive to environmental change (Oulehle et al. 2011). Soil litter monitoring at BRF estimates that approximately 0.5 kg C per square meter is stored in soil litter and organic matter (Bower 2019). Soil carbon sampling to 60 cm of depth on the long term plots at Black Rock Forest estimates an additional 18.8 kg C per square meter on average (Palmer 2020). Adding these estimates to the estimate of live biomass (9.75 kg C per square meter), I estimate a total ecosystem C is approximately 29.05 kg C per square meter, including soil, soil litter, and live biomass of the study species. However, this estimate may vary based on soil depth, forest productivity, and climate.

Some forests experience a decline in overall soil carbon and rates of soil carbon sequestration as they mature into steady-state forests with altered leaf litter dynamics and decreased fine root decomposition (Lovett et al. 2016). There is some indication that deacidification of forest soils over the past 20 years may contribute to decreased soil carbon

sequestration, as well as changing the species composition of recruited seedlings (Oulehle et al. 2011; Zarfos et al. 2019). All of these factors, which have been observed in other northeastern forests, may also be occurring at Black Rock, reducing the total carbon sequestration of the long-term plots.

The decay of dead woody debris is another important factor in the forest carbon cycle. Woody debris in oak-dominant forest is typically estimated as 5% (low) to 12% (high) of aboveground biomass (Schuster 2008). Using the figure of 7.8 kg C per square meter stored in aboveground dry biomass in live trees, woody debris adds between 0.39 kg C and 0.94 kg C per square meter. Adding this to the estimate in the previous paragraph yields an estimate of 29.44-29.99 kg C per square meter including live biomass, soil litter, soil, and woody debris from study species. This does not account for woody debris from species not included in this study, including species that have experienced significant recent mortality such as chestnut and hemlock.

Table 3. Estimates of the size of carbon reservoirs at Black Rock Forest and summary estimate of total carbon storage (excluding non-study tree species) on BRF's long term plots.

Carbon Reservoir	**Quantity (estimated kg C per m^2)**
Live Aboveground Biomass	7.80
Live Belowground Biomass	1.45
Dead Woody Debris	0.39-0.94
Soil Litter and Organic Matter	0.50
Soil Below O Horizon	18.81
Total Ecosystem C	29.44-29.99

Data collected on the decomposition of standing and fallen dead wood on the long-term plots at Black Rock Forest shows that black birch generally progresses through the decomposition process more rapidly than either species of oak (Schuster 2015). This suggests that increased birch dominance in the canopy and a rise in the proportion of carbon stored in birch could change not only the total amount of carbon sequestered at BRF but also how rapidly that carbon is released to the atmosphere after tree mortality.

Forest changes at BRF and carbon sequestration

The density, species composition, and size of trees on the long-term plots at BRF have changed significantly since 1931, when the plots were first measured. Three species have left the forest, and seven have arrived through climate shifts or human introduction. The density of individual trees has been cut in half and the mean tree basal area has doubled (Schuster et al. 2008). Black birches in particular have increased in density and size, especially during droughts and outbreaks of insect infestation (Schuster 2012). All of these changes have had significant impacts on carbon sequestration at BRF.

When the long-term plots were established, oak was by far the dominant species in the forest. Red oak and chestnut oak remain the majority in the canopy (Schuster et al. 2008). However, oak seedling recruitment and presence in the understory has dropped dramatically since 1931. This could be due to a variety of factors, including the poor performance of oak seedlings in shade, competition with seedlings more adapted to later-successional forests, and preferential browsing of acorns and oak seedlings by deer in the forest (Drury and Runkle 2006).

The lack of oaks as seedlings, saplings, and understory trees leads to a cycle in which the understory does not grow into the canopy as typically occurs after a larger tree mortality or forest

disturbance. This accounts for the decline in chestnut oak biomass since 1965; when mature chestnut oaks die or are disturbed, younger chestnut oaks do not replace them (Schuster et al. 2008). Rather, other species such as birch and maple replace them in the canopy layer. The carbon stored in the mature oaks is released as decomposition progresses, and the overall quantity of carbon sequestered in live aboveground biomass in the forest declines.

Black birch, because of its adaptability and its success in the understory at BRF, is slowly but steadily becoming a significant canopy tree. It outcompetes oaks, maples, and other historically more dominant species during events such as drought that other trees cannot tolerate (Schuster et al. 2008). Birch wood is lower in density than oak wood, stores slightly less carbon per kilogram of dry biomass, and decomposes more rapidly when mortality occurs (Schuster 2015; Wutzler et al. 2011). Although black birch appears to comprise a relatively small proportion of the overall biomass of the long-term plots at BRF, its increasing prominence combined with a decline in biomass in mature red and chestnut oaks could have serious implications for carbon storage at BRF in the future.

Comparison of BRF allometric equations to prior published equations

The improved estimates of aboveground biomass due to location-specific, species-specific allometric equations from this research give a better understanding of how shifts in oak and birch dominance may affect carbon sequestration. The new BRF equations have a slightly stronger correlation with the observed biomass of BRF trees than either Brenneman et al. (1978) or Jenkins et al. (2003) as evidenced by slightly higher R^2 values in the linear regressions (Appendix B).

The greatest difference in biomass predictions from generating new location-specific, species-specific equations is estimates of chestnut oak biomass. The Brenneman et al. (1978) equation significantly overestimates chestnut oak biomass at BRF. For a tree with a 45 cm diameter, the biomass estimates from the Brenneman et al. equation and the BRF equation differ by almost 500 kg. The equation provided in Jenkins et al. (2003) also overestimates, but the variation from the BRF equation is not statistically significant. The reasons for the difference between the Brenneman et al. (1978) equation and the BRF equation are unclear. They could include differences in soil and climate, which can significantly impact the root distribution and growth pattern of trees. There could also be some variance in sampling technique. By using the Brenneman et al. (1978) equation to make chestnut oak biomass estimates, BRF has likely been significantly overestimating the quantity of carbon sequestered in chestnut oak in the long term plots. This could cause the decline in chestnut oak biomass and carbon sequestration from 1965 on to appear less severe.

Both the Brenneman et al. (1978) and Jenkins et al. (2003) equations underestimate black birch biomass for BRF. The difference between black birch biomass calculated using the BRF and Brenneman et al. (1978) equations and biomass calculated using the Jenkins et al. (2003) equation is statistically significant. For a black birch with a 35 cm diameter, the Jenkins et al. equation differs from the BRF equation by approximately 100 kg. Using the underestimating equations, particularly Jenkins et al. (2003), to model carbon sequestration in black birch on the long-term plots may have caused the increase in black birch biomass to appear less significant relative to the biomass of the two oak species. Birch is less carbon-dense than oak; a kilogram of birch biomass stores slightly fewer grams of C than a corresponding kilogram of oak biomass.

Increasing the share of biomass allocated to birch changes estimates of how much carbon is stored at BRF.

The differences between the equations from literature and the BRF equations are significant enough that they impact biomass estimates in chestnut oak, red oak, and black birch on a forest-wide scale. The direction of misestimation differs by species. For chestnut oak, both equations overestimate BRF biomass; for black birch, they underestimate. Tree growth and carbon sequestration are sensitive to environmental conditions like climate, photoperiod, soil type, and ecological factors such as the presence of wildlife, pests, and disease. Therefore, allometric equations developed for different regions or different scales may not adequately estimate biomass and carbon stocks. Forest managers and other stakeholders who are interested in managing forested lands for carbon sequestration should consider working to generate their own species-specific, location-specific allometric equations if labor and the scale of the forest permit.

Conclusions and Recommendations

This study has several implications regarding forest management for carbon storage. The first is an understanding of how tree growth and biomass accumulation at Black Rock Forest might differ from trees of the same species elsewhere in North America. Varying environmental conditions do not affect all species uniformly and understanding how biomass accumulation in each species differs on regional and local levels is key to understanding how carbon moves through forests.

The differences between locally specific and more general allometric equations, in addition to helping us understand how trees at BRF differ from trees elsewhere, also makes a

case for the generation of other location- and species-specific allometric equations where feasible. Foresters who are interested in accurately assessing their aboveground live carbon stocks could potentially significantly alter their estimates by developing their own models using trees grown under the same environmental conditions. Forests where long-term forestry data such as DBH has been collected could particularly benefit from this. If the development of unique allometric equations is not feasible, this study also makes a case for applying region- and species-specific equations found in the literature where they exist.

Finally, looking at how species composition has possibly affected and will continue to affect carbon storage at BRF gives foresters in similar ecosystems an idea of what they might expect from forest change. While the biomass of black birch at BRF is still small relative to the biomass of oak, increasing birch dominance has been associated with an overall plateau in carbon sequestration in the long-term plots. Other regions of the northeast that are experiencing reduced oak seedling recruitment and rising black birch presence might use allometric equations to assess whether this change is having an impact on their carbon storage rates and quantities. More generally, forest managers could be aware of other shifts in species composition and take steps to assess how changes in their forest community might affect biomass accumulation and carbon sequestration.

Temperate forests are an essential element of the global carbon cycle. Although managing existing forests on a local level for carbon sequestration plays a relatively small role in mitigating atmospheric carbon from anthropogenic emissions, retaining the role of temperate forests as carbon sinks could play a significant part in adjusting atmospheric carbon on a worldwide scale. The first steps in managing carbon sequestration are accurately estimating how

much carbon actually exists in temperate forests, understanding how regional variation affects carbon storage estimates, and evaluating how forest change might affect carbon storage in the future.

References

Ashton, M. S., M. L. Tyrrell, D. Spalding, and B. Gentry. 2012. *Managing Forest Carbon in a Changing Climate*. New York: Springer.

Bormann, F. H. and G. E. Likens. (1979). *Pattern and Process in a Forested Ecosystem*. Springer-Verlag: New York Inc.

Bower, P. (2019). *Soil litter carbon on BRF long-term plots*. Unpublished data.

Bradford, J.B., Weishampel, P., Smith, M., Kolka, R. Birdsey, R.A., Ollinger, S.V., Ryan, M.G. (2010). Carbon pools and fluxes in small temperate forest landscapes: Variability and implications for sampling design. *Forest Ecology and Management 259*, 1245-1254.

Brenneman, B.B., Frederick, D.J., Gardner, W.E., Schoenhofen, L.H. and Marsh, P.L. (1978). Biomass of species and stands of West Virginia hardwoods. In *Proceedings of Central Hardwood Forest Conference* II. P.E. Pope (ed.). Purdue University, 159–178.

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

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

Dixon, R., Brown, S., Houghton, R., Solomon, A., Trexler, M., and Wisniewski, J. (1994). Carbon Pools and Flux of Global Forest Ecosystems. *Science, 263*(5144), 185-190.

Drury, S.A. and J.R. Runkle. (2006). Forest vegetation change in southeast Ohio: do older forests serve as useful models for predicting the successional trajectory of future forests? *Forest Ecology and Management 223*, 200–210.

Eswaran, H., Reich, PF., Kimble, J., Beinroth, FH., Padmanabhan, E., Moncharoen, P. (2000). Global Carbon Stocks. In: *Global Climate Change and Pedogenic Carbonates*, Ed. Lal, R. Boca Raton, Fl: Lewis Publishers, 15-26.

Fahey, T. J., T. G. Siccama, C. T. Driscoll, G. E. Likens, J. Campbell, C. E. Johnson, J. D. Aber, J. J. Cole, M. C. Fisk, P. M. Groffman, R. T. Holmes, P. A. Schwarz and R. D. Yanai. (2005). The biogeochemistry of carbon at Hubbard Brook. *Biogeochemistry 75*(1),109-176.

Fahey, T. J., J. W. Hughes, M. Pu and M. A. Arthur. (1988). Root decomposition and nutrient flux following the whole-tree harvest of northern hardwood forest. *Forest Science 34*(3),744-768.

Falxa-Raymond, N, Patterson, A.E., Schuster, W.S.F., and Griffin, K.L. (2012). Oak loss increases foliar nitrogen, δ15N and growth rates of Betula lenta in a northern temperate deciduous forest. *Tree Physiology,* 00, 1-10.

Fatemi, F. R., Yanai, R.D., Hamburg, S.P., Vadeboncoeur, M.A., Arthur, M.A., Briggs, R.D., and Levine, C.R. (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 Forestière,* 41, 881-891.

IPCC. (2018). *Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A.

Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., and Birdsey, R.A. (2013). Comprehensive database of diameter-based biomass regressions for North American tree species. *General Technical Report NE-319*. Washington, D.C.: US Department of Agriculture.

Li, H. K., and Zhao. P.X. (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.

Lovett, G. M., M. A. Arthur and K. F. Crowley. (2016). Effects of calcium on the rate and extent of litter decomposition in a northern hardwood forest. *Ecosystems 19*(1), 87-97.

Monteith, L. (1979). Whole tree weight tables for New York. *Res. Rep. 40, Applied Forestry Research Institute, Syracuse, NY*, 67.

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.

Oulehle, F., C. D. Evans, J. Hofmeister, R. Krejci, K. Tahovska, T. Persson, P. Cudlin, and J. Hruska. (2011). Major changes in forest carbon and nitrogen cycling caused by declining sulphur deposition. *Global Change Biology 17*(10), 3115-3129.

Palmer, G. (2020). Soil organic carbon storage and soil recovery from acidification in a northern temperate deciduous forest. (Unpublished senior thesis). Barnard College. New York.

Schuster, W.S.F., Griffin, K.L., Roth, H., Turnbull, M.H., Whitehead, D., and Tissue, D.T. (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.

Schuster, W.S.F. (2012). Forest ecology. In *The Highlands: Critical Resources, Treasured Landscapes*. Lathrop, R.G. (Ed.). Rutgers University Press: Rutgers, NJ.

Schuster, W.S.F. (2015). *Snag and deadfall decomposition on BRF long-term plots*. Unpublished data.

Sillett, S.C., Van Pelt, R., Carroll, A.L., and Coonan, E.J. (2019). Allometric equations for *Sequoia sempervirens* in forests of different ages. *Forest Ecology and Management, 433*, 349-363.

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

Townsend, D. S., Seva, J.S., Hee-Seagle, C., and Mayers, G. (2002). Structure and Composition of a Northern Hardwood Forest Exhibiting Regeneration Failure. *Bartonia*, 61, 1–13.

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

Wutzler, T., Profft, I. and Mund, M. (2011). Quantifying tree biomass carbon stocks, their changes and uncertainties using routine stand taxation inventory data. *Silva Fennica, 45*(3), 359–377

Zarfos, M.F., Dovciak, M., Lawrence, G.B., McDonnell, T.C., and Sullivan, T.J. (2019). Plant richness and composition in hardwood forest understories vary along an acidic deposition and soil-chemical gradient in the northeastern United States. *Plant and Soil 438*, 461-477.

Appendices

Appendix A. Full tree felling data for chestnut oak (*Q. prinus*), red oak (*Q. rubra*) and black birch (*B. lenta*) at Black Rock Forest 2000-2019. Missing data (from incomplete BRF records between 2000-2014) indicated with a dash.

Table 1. Chestnut oak (*Q. prinus*)

Species	*Year*	*DBH (cm)*	*Wet Weight (kg)*	*Dry Weight (kg)*	*Drying Factor*
Q. prinus	2011	17.27	-	134	-
Q. prinus	2010	26.92	-	383	-
Q. prinus	2002	30.48	737	443	0.587
Q. prinus	2005	30.99	836	513	0.591
Q. prinus	2009	34.29	-	841	-
Q. prinus	2000	35.56	1117	915	0.819
Q. prinus	2019	40.01	1372	1102	0.810
Q. prinus	2014	42.30	-	1301	-
Q. prinus	2011	43.43	-	866	-
Q. prinus	2012	47.24	-	1555	-
Q. prinus	2013	48.77	-	1417	-

Table 2. Red oak (*Q. rubra)*

Species	*Year*	*DBH (cm)*	*Wet Weight (kg)*	*Dry Weight (kg)*	*Drying Factor*
Q. rubra	2011	12.70	-	49	-
Q. rubra	2011	19.81	-	188	-
Q. rubra	2011	23.37	-	279	-
Q. rubra	2010	23.88	-	293	-
Q. rubra	2011	29.72	-	536	-
Q. rubra	2002	34.80	1088	632	0.581

Q. rubra	2006	36.58	-	799	-
Q. rubra	2004	39.62	1706	952	0.557
Q. rubra	2007	42.42	-	1211	-
Q. rubra	2003	43.94	1727	855	0.495
Q. rubra	2002	46.99	2509	1379	0.549
Q. rubra	2013	48.00	-	1856	-

Table 3. Black birch (*B. lenta*).

Species	*Year*	*DBH (cm)*	*Wet Weight (kg)*	*Dry Weight (kg)*	*Drying Factor*
B. lenta	2015	1.52	0.9	0.4	0.490
B. lenta	2015	2.16	1.9	1.1	0.520
B. lenta	2015	2.29	2.1	1.2	0.560
B. lenta	2015	3.68	6.0	3.0	0.591
B. lenta	2015	6.99	27	15	0.593
B. lenta	2015	9.63	54	29	0.551
B. lenta	2015	14.1	152	84	0.562
B. lenta	2015	18.44	345	203	0.590
B. lenta	2015	20.73	330	215	0.650
B. lenta	2015	21.67	416	245	0.590
B. lenta	2015	24.69	582	318	0.540
B. lenta	2015	29.82	921	492	0.530
B. lenta	2015	31.32	989	593	0.613
B. lenta	2016	35.5	1368	847	0.632
B. lenta	2016	38.5	1642	1033	0.600
B. lenta	2015	39.8	2017	1230	0.610
B. lenta	2018	36.95	1423	930	0.650
B. lenta	2018	33.02	979	626	0.639
B. lenta	2019	40.23	1455	1129	0.770
B. lenta	2019	32.84	1341	844	0.629

Appendix B. Scatter plots charting observed biomass for each sample tree against calculated biomass using each equation (BRF equation, Jenkins et al. 2003, Brenneman et al. 1978). The strength of the linear relationship (R^2) is shown on each chart.

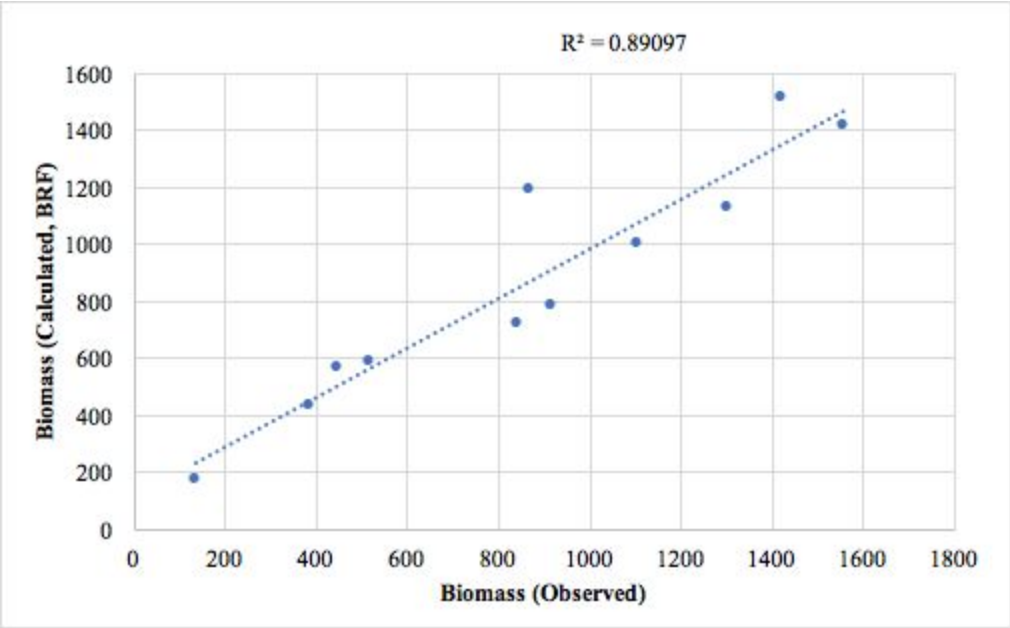

Figure 1. Observed biomass vs. calculated biomass (BRF equation) for chestnut oak. R^2=0.891.

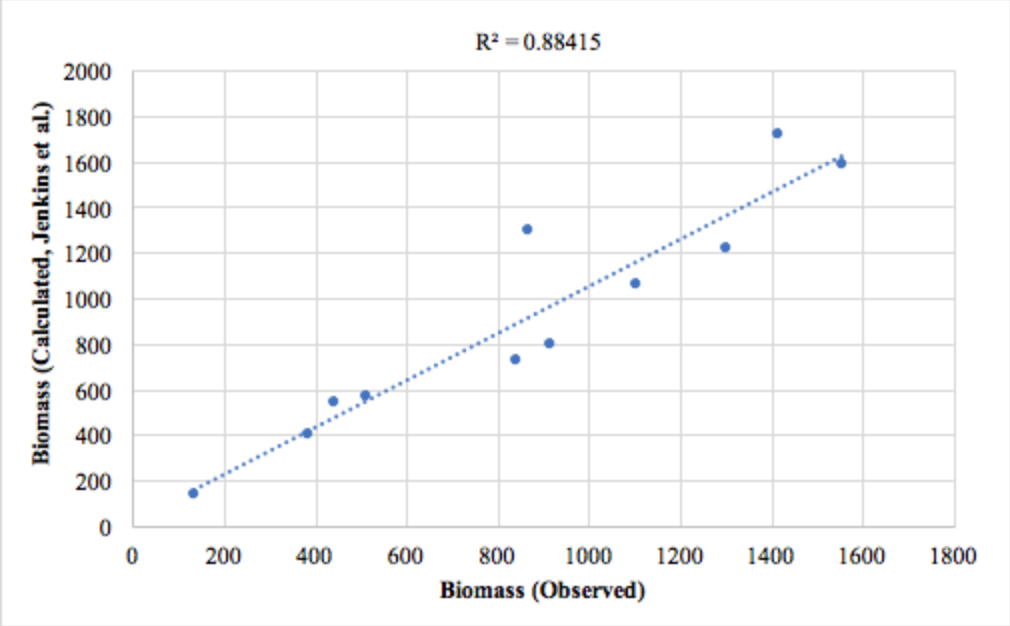

Figure 2. Observed biomass vs. calculated biomass (Jenkins et al. 2003) for chestnut oak. R^2=0.884.

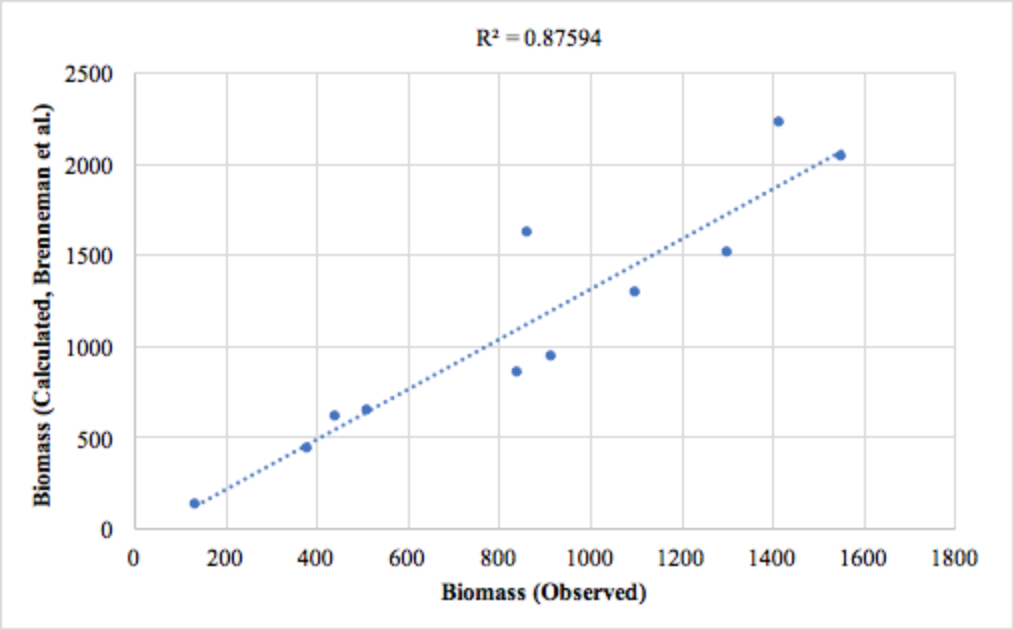

Figure 3. Observed biomass vs. calculated biomass (Brenneman et al. 1978) for chestnut oak. R^2=0.875.

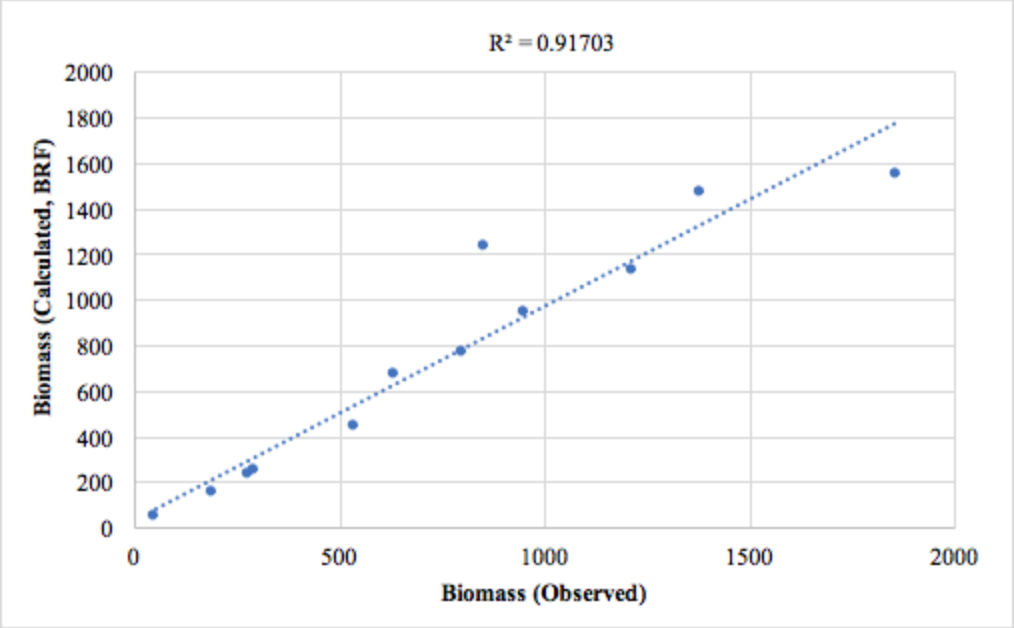

Figure 4. Observed biomass vs. calculated biomass (BRF equation) for red oak. R^2=0.917.

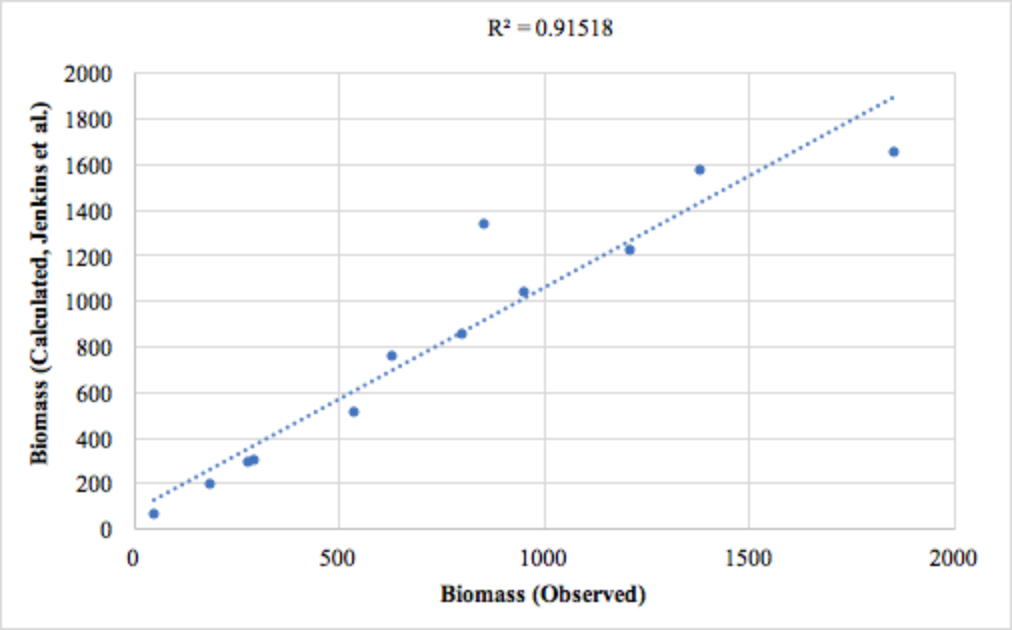

Figure 5. Observed biomass vs. calculated biomass (Jenkins et al. 2003) for red oak. R^2=0.915.

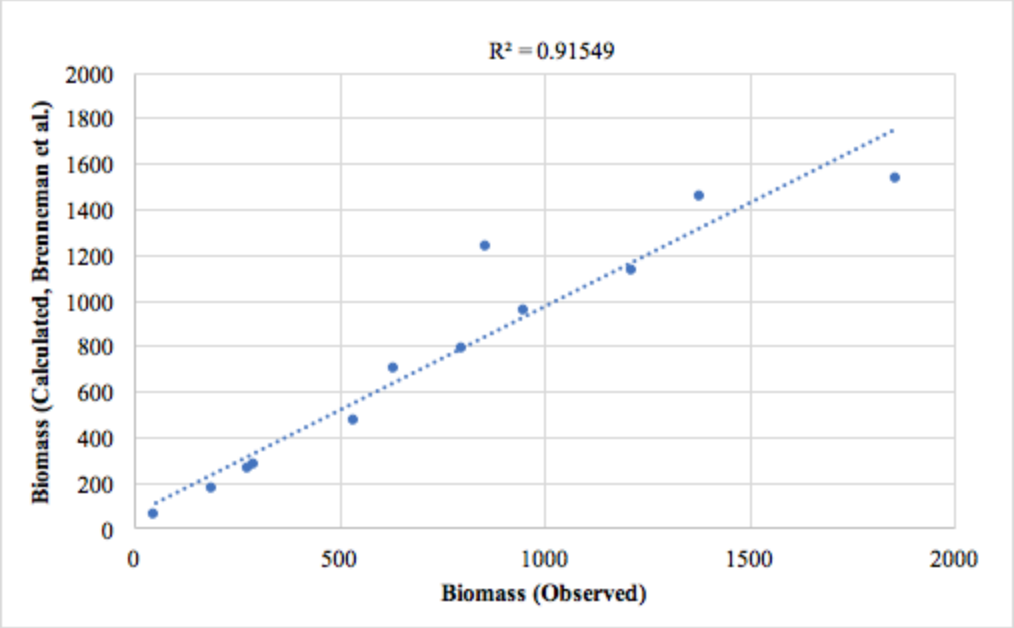

Figure 6. Observed biomass vs. calculated biomass (Brenneman et al. 1978) for red oak. R^2=0.915.

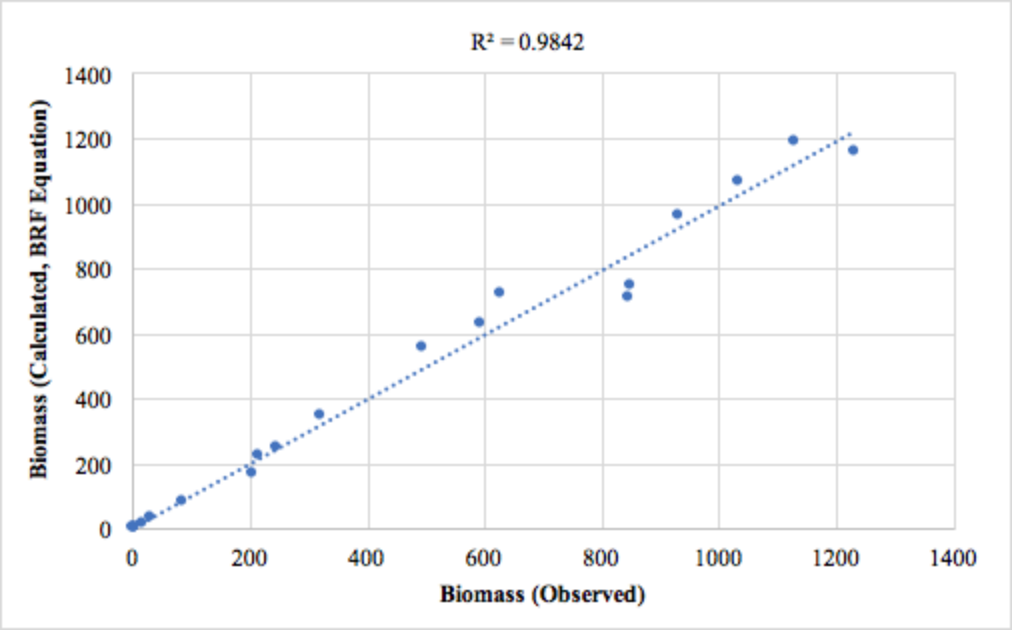

Figure 7. Observed biomass vs. calculated biomass (BRF equation) for black birch. R^2=0.984.

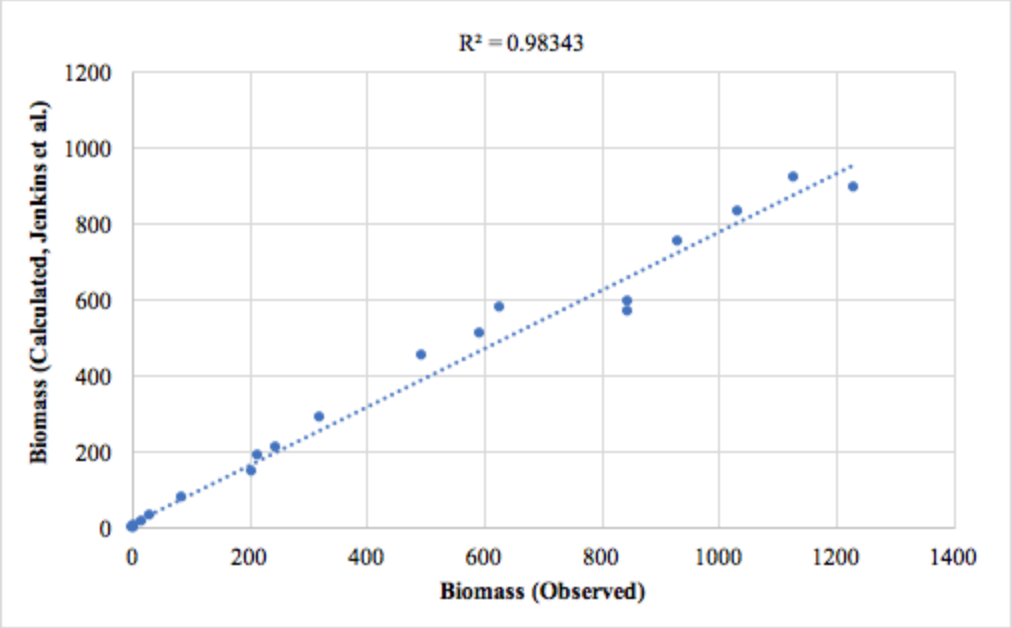

Figure 8. Observed biomass vs. calculated biomass (Jenkins et al. 2003) for black birch. R^2=0.983.

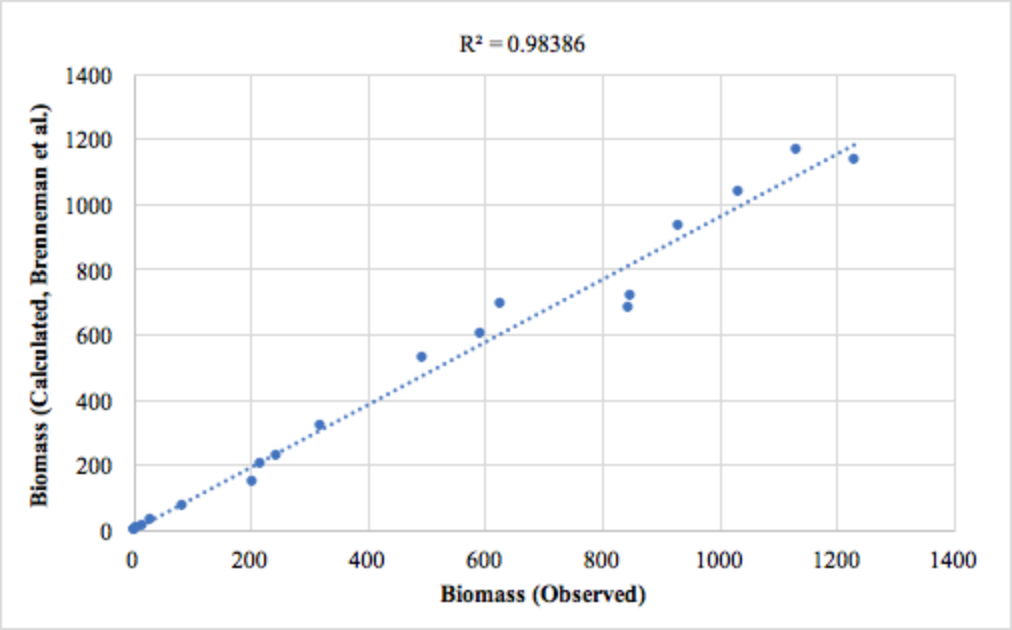

Figure 9. Observed biomass vs. calculated biomass (Brenneman et al. 1978) for black birch. R^2=0.983.

Appendix C. Full one-way ANOVA with post-hoc Tukey HSD test results testing the statistical significance of variance between equations within species and size classes. Significant differences are highlighted. Sample A is the BRF equation, Sample B is the Jenkins et al. (2003) equation, and Sample C is the Brenneman et al (1978) equation.

Table 1. Chestnut oak (*Q. prinus*) DBH<35 cm. Because of the lack of a significant p-value, no Tukey post-hoc HSD test was conducted.

Source	Sum of squares	Degrees of freedom	Mean square	F statistic	p-value
treatment	3,895.3578	2	1,947.6789	0.0443	0.9569
error	395,877.9551	9	43,986.4395		
total	399,773.3128	11			

Table 2. Chestnut oak (*Q. prinus*) DBH>35 cm.

Source	Sum of squares	Degrees of freedom	Mean square	F statistic	p-value
treatment	618,856.7297	2	309,428.3648	4.4962	0.0443
error	619,378.4184	18	68,819.8243		
total	1,238,235.1480	20			

Treatment pair	Tukey HSD Q statistic	Tukey HSD p-value	Tukey HSD interference
A vs. B	1.0833	0.7212591	insignificant
A vs. C	4.0925	0.0424942	p<0.05
B vs. C	3.0092	0.1385229	insignificant

Table 3. Red oak (*Q. rubra*) DBH<35 cm. Because of the lack of a significant p-value, no Tukey post-hoc HSD test was conducted.

Source	Sum of squares	Degrees of freedom	Mean square	F statistic	p-value
treatment	4,393.0111	2	2,196.5055	0.0915	0.9132

error	287,967.7425	12	23,997.3119		
total	292,360.7536	14			

Table 4. Red oak (*Q. rubra)* DBH>35 cm. Because of the lack of a significant p-value, no Tukey post-hoc HSD test was conducted.

Source	Sum of squares	Degrees of freedom	Mean square	F statistic	p-value
treatment	37,072.9911	2	18,536.4955	0.2083	0.8143
error	1,335,034.9321	15	89,002.3288		
total	1,372,107.9231	17			

Table 5. Black birch (*B. lenta*) DBH<3 cm. Because of the lack of a significant p-value, no Tukey post-hoc HSD test was conducted.

Source	Sum of squares	Degrees of freedom	Mean square	F statistic	p-value
treatment	791.5464	2	395.7732	0.0154	0.9847
error	849,190.2595	33	25,733.0382		
total	849,981.8059	35			

Table 6. Black birch (*B. lenta*) DBH>35 cm.

Source	Sum of squares	Degrees of freedom	Mean square	F statistic	p-value
treatment	144,824.9944	2	72,412.4972	7.7193	0.0112
error	84,426.1486	9	9,380.6832		
total	229,251.1430	11			

Treatment pair	Tukey HSD Q statistic	Tukey HSD p-value	Tukey HSD interference
A vs. B	5.0888	0.0143072	p<0.05
A vs. C	0.6114	0.8999947	insignificant
B vs. C	4.4773	0.0278134	p<0.05

Table 7. Black birch (*B. lenta*) DBH>30 cm. Because of the lack of a significant p-value, no Tukey post-hoc HSD test was conducted.

Source	Sum of squares	Degrees of freedom	Mean square	F statistic	p-value
treatment	166,053.0266	2	83,026.5133	1.9145	0.1723
error	910,699.1012	21	43,366.6239		
total	1,076,752.1277	23			