1. *Which factors are important for allometric relationships when assumptions of linearity are relaxed for northern hardwood* 
   1. *Challenge to set up: assumptions about the model structure*
   2. *Identify a small number of approaches – physiology, vs imposing linear relationships on a log scale*
2. *Is there a difference in allometric relationships between young stands and old stands.*
   1. *Challenge to set up: there may be heterogeneity in these relationships*
   2. *Make clear that this is not about size, but age.*
   3. *Have people looked for heterogeneity?* 
      1. *Could be specific or more general*
3. *How can we propagate uncertainty into predictions?*

Be sure to introduce everything in introduction.

Establish/characterize novelty

Opening: overall problem – allometry is important and there are challenges.

A few paragraphs elaborating challenges and prior work that sounds important.

End – introduce my study system and questions.

Critical

***Abstract***

***Introduction***

The ability to accurately estimate tree biomass is essential for scientific, economic and policy purposes. Concerns about global climate change have led policy-makers to focus efforts on maximizing the carbon stocks and sequestration abilities of forests (Domke et al. 2012; Eggleston et al. 2006; Van Breugel et al. 2011). Thereby, effective policy design requires that forest carbon stocks can be accurately and cheaply estimated. Furthermore, forest carbon-offset trading on emerging carbon markets ties estimates of carbon stocks to monetary transactions, amplifying the implications of misestimation (Kerchner et al. 2015; Newell et al. 2013). Since forest carbon cannot be directly measured, carbon stocks are most often estimated using allometric models (Jenkins et al. 2003; Van Breugel et al. 2011). Allometric models, first described by Huxley and Tessier in 1936, relate low-dimensional, easily-obtained measurements such as height and diameter, to difficult and destructive measurements such as individual tree biomass (Huxley and Tessier 1936). Difficulty in obtaining accurate data, and a lack of consensus on methodology lead to significant uncertainty and inaccuracy in both biomass and carbon estimates, necessitating the exploration of this problem using novel statistical techniques (Sileshi 2014; Jenkins et al. 2003; Van Breugel et al. 2011).

One major source of uncertainty in allometric models lies in the assumptions made about basic model structure (Sileshi 2014; Van Breugel et al. 2011). Most commonly, allometric scaling relationships adopt the form of a power-function, owing to the apparent linearity of allometric relationships plotted on a log-log scale (Picard et al. 2014; Sileshi 2014). These model forms are referred to as “simple” allometric models (Huxley and Tessier 1936). “Complex” allometric models, on the other hand, specify relationships that are non-linear on a double logarithmic scale (Huxley and Tessier 1936; Picard 2015). A third method of allometric modelling invokes a priori assumptions about the physiological relationships between tree components (West et al. 1999; MacFarlane 2015). This paper focuses on the first two types of models, whose formulation are driven by statistical analysis rather than theoretical deduction. The volume of literature touting each of these methods has created an overwhelming predicament for managers, economists and policy-makers attempting to choose between and apply these models.

The use of a Generalized Additive Model (GAM) allows us to relax the assumption of linearity adopted by “simple” allometric models, without specifying an alternative, non-linear model form as is done with “complex” allometric models. This is made possible by the non-parametric nature of GAMs, which relate the response variable (tree biomass) to the predictor variables (diameter and height) via unknown smoothing functions (Hastie and Tibshirani 1987). This flexibility allows the relationship between the predictor and response variables to break the assumptions that accompany “simple” and “complex” model specifications and potentially lead to a better fit to the data (Hastie and Tibshirani 1987). Given the economic and social importance of properly estimating carbon stocks, such improvements to the accuracy of allometric models is critical.

Most models incorporate heterogeneity in allometric relationships among species or groups of similar species (Jenkins et al 2013; Picard et al 2015). However, few account for variation in allometric scaling relationships beyond species and diameter. Evidence suggests that incorporating additional sources of heterogeneity into allometric models could improve their accuracy (Weiskittel et al. 2015; Fatemi et al. 2011). For example, studies detailing differential growth patterns among trees of different ages suggest that allometric relationships may vary according to tree age (Bond 2000; Fatemi et al. 2011).

Another significant barrier to the development of accurate allometric models is the difficulty and expense involved in directly measuring tree biomass (Van Breugel et al. 2011; Sileshi 2014; Jenkins et al. 2003). In order to measure the biomass of a single tree, it must be cut-down, dissected, transported to a lab, dried and then weighed (Whittaker and Woodwell 1968; Fatemi et al. 2011). The destructivity and inconvenience of this process prohibits the collection of large datasets. This implicit bound on sample-size limits the degree of certainty in models derived from single-study datasets. This study addresses this difficulty in data collection by synthesizing multiple, comparable datasets collected in the White Mountains of New Hampshire over the course of several decades.

Through the formulation of a Generalized Additive Model for allometric relationships in the northern hardwood forests of New Hampshire, this study seeks to answer several questions: (1) Which factors are important for allometric relationships when assumptions of linearity on a log-log scale are relaxed? (2) Is there a difference in allometric scaling relationships between trees in young and old stands? Answering these questions will help improve the accuracy of this particular allometric model, guide the development of future models for a more diverse set of regions and species, and aid managers, economists and policymakers attempting to apply allometric scaling relationships.

***Methods***

***Results***

***Discussion***

***Conclusion***

***Citations***

Bond 2000

*Bond, B. J. (2000). Age-related changes in photosynthesis of woody plants. Trends in plant science, 5(8), 349-353.*

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*Hastie, T., & Tibshirani, R. (1987). Generalized additive models: some applications. Journal of the American Statistical Association, 82(398), 371-386.*

Huxley and Tessier 1936

*Huxley, J.S., Teissier, G., 1936. Terminology of relative growth. Nature 137, 780–781.*

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Sileshi et al 2014

*Sileshi, G. W. (2014). A critical review of forest biomass estimation models, common mistakes and corrective measures. Forest Ecology and Management, 329, 237-254.*

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*fractal geometry and allometric scaling of organisms. Science 284 (5420),*

*1677–1679.*

***COMPELS***

***What should introduction focus on/include?***

*Importance of predicting tree biomass*

* Carbon stock determination – Carbon Market/Offset sales (may belong more in the intro)
* Inability to directly measure tree biomass without great expense and destruction

*Difficulty of accurately predicting tree biomass*

* Complex architecture of trees (especially hardwoods)
* Difficulty in collecting accurate data at large volumes
* Generalizability

*Historic statistical models for allometry*

* Linear regression most common
* No unified methodology – leads to great deal of uncertainty/equation bias in estimates.
  + Specifically with FIA data (Chojnacky paper)
* Dimensional Analysis (Whittaker etc)
* Power function form (simple)
* Simple vs complex allometry

*Information about Hubbard Brook Experimental Forest (HBEF) and specifically the study sites used.*

* Northern hardwood forests in general
* HBEF/WMNF
* Provide Map?

*Information about previous studies in which data was collected.*

* Fahey
* Siccama
* Whittaker
* Fatemi
* Battles
* BattlesRock

***Questions for Perry:***

Should I be worried about collinearity when using both height and diameter as predictors?

Should I do Cross-Validation to check for over-fitting in GAM?

Use Specific-Gravity as a continuous predictor?

***From Silviculture Term Paper***

The development of predictive models relating low-dimensional tree measurements such as diameter and height to biomass is of great academic and practical interest. Such models seek to overcome the difficulty of measuring biomass directly in order provide the utility of these measurements for research and management decisions (Whittaker 1974; Weiskittel et al 2015). Additionally, concerns over global carbon emissions and the development of carbon markets internationally have resulted in increased interest in the ability to accurately and cheaply determine forest carbon stocking (Weiskittel et al 2015). The development of robust allometric models is limited by the cost and difficulty of accurately measuring tree biomass with necessary replication (Whittaker 1974). This has led researchers to develop a wide-variety of methods for estimation.

Sileshi paper points out importance of documenting uncertainty about parameters – how do I do this?