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Historic Log Buildings as Archives of Past Forest Ecology

Kristen K. de Graauw

West Virginia University, kkdegrauw@mix.wvu.edu

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Historic Log Buildings as Archives of Past Forest Ecology

Kristen K. de Graauw

Dissertation submitted
to the Eberly College of Arts and Sciences
at West Virginia University

in partial fulfilment of the requirements for the degree of

Doctor of Philosophy in
Geography

Amy Hessler, Ph.D., Chair
Steven Kite, Ph.D.
Stockton Maxwell, Ph.D.
Brenden McNeil, Ph.D.
Shikha Sharma, Ph.D.

Department of Geology and Geography

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Abstract

Historic Log Buildings as Archives of Past Forest Ecology

Kristen K. de Graauw

This dissertation is composed of three separate but related manuscripts with the common theme of using historic log buildings from the central Appalachian Mountain region of eastern North America as ecological archives. In Chapter 1, I explore the biases, limitations, and ecological applications of tree-ring data from historic log buildings. European immigrants selected trees from a forested stand based on species, log sizes, and construction locations. Despite this selection bias, ecological information can be gleaned from historic log buildings, which offer a complementary record of past forest ecology and represent a site type that is not often associated with old-growth trees; the upland forest. Chapter 1 was published in *Dendrochronologia* in 2017. In Chapter 2, my coauthor and I investigate reforestation following the depopulation of Indigenous Peoples in the central Appalachian Mountain region by comparing recruitment, early radial growth, and growth releases of historic logs and old-growth trees. Results from most, but not all, historic log buildings suggest that these trees were felled from second-growth forests supporting the previously hypothesized idea that depopulation of Indigenous Peoples led to forest regrowth on abandoned land. Chapter 2 is currently in press at *Journal of Biogeography* (10/04/19). In Chapter 3, I use carbon isotopes in tree rings from a historic log building and modern live trees from the same site to demonstrate similar responses of trees to changes in moisture during the pre-industrial (pre-1850 CE) and post-industrial (post-1850 CE) periods. Changes in mean $\Delta^{13}\text{C}$ from dry to wet years is similar for historic and modern samples suggesting that historic wood archives are a reliable tree-ring isotope source for tracking environmental changes of the past several centuries.

Dedication

*To Stella.
My best girl, always.*

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Introduction

After two failed attempts to begin research on vastly different projects, one on eastern hemlock (*Tsuga canadensis*) in eastern North America and the other on early nomadic empires in Mongolia, I realized that I needed to invest in a project that felt wholly mine. My research interests lie in dendrochronology (tree-ring research) and forest ecology, my scientific ‘hobby’ is dendroarchaeology (tree-ring dating of historic log buildings), and I am fascinated by history, archaeology, and folklore. I set out to combine my interests in a new subdiscipline of dendrochronology, now called “dendro-archaeo-ecology” (credit for name, Trouet *et al.*, 2018). Thus, the following dissertation is centered around the investigation of past human-environment interactions and forest dynamics from the ‘archived’ tree-ring records in historic log buildings.

My dissertation “Historic Log Buildings as Archives of Past Forest Ecology” is composed of three related manuscripts, two of which are written for scientific journals. The specific topics evolved and/or deviated from my original objectives as I progressed through my research, but they never faltered from the central theme of investigating the use of historic logs to understand past forest environments. As this research was novel, it behooved me to begin with a descriptive introduction, much like early geographical research. My first chapter, published in 2017 in *Dendrochronologia*, serves as this introduction to ‘dendro-archaeo-ecology’ as a case study in eastern North America, and outlines the biases, limitations, and benefits of using historic log buildings to understand past forests. In this chapter I suggest potential avenues for future research, but as I discovered while writing the second chapter, the possibilities of scientific exploration extend well beyond my initial suggestions.

The second chapter of my dissertation began as an investigation of the disturbance history of forests during and after European immigration in the central Appalachian Mountain region. As I was completing my disturbance reconstruction methods and preparing to discuss Euro-American land-use practices in the 1700s–1800s, a highly publicized scientific article captured my attention. The authors (Koch *et al.* 2019) suggested that land-use practices of peoples indigenous to the Americas were so extensive that when European diseases wiped out much of the population there was widespread reforestation which ultimately altered global climate during the Little Ice Age. Their model of climate alteration was contingent upon massive reforestation, for which no empirical evidence was available. This prompted me to wonder if historic log buildings might hold evidence of reforestation in their annual rings. Thus, the chapter on European land use then became the chapter on land use of Indigenous Peoples of the central Appalachian Mountain region and an investigation of reforestation following field abandonment. This chapter was accepted to *Journal of Biogeography* in October 2019 and is currently in press.

The third chapter of my dissertation provided me an avenue to acquire a new skillset and to use tree-ring data from historic log buildings in yet another new way. In this chapter, I use carbon isotopes from tree rings in historic logs and modern trees from the same site, though separated by time, to determine if logs from historic buildings are a reliable dendroisotopic record. I found that mean $\Delta^{13}\text{C}$ is similar for historic and modern samples and it is more positive in wet years which indicates that historic and modern trees discriminate more against atmospheric ^{13}C

(favoring the lighter ^{12}C) in wet years when they are less water stressed. While there were several challenges in preparing samples for isotopic analysis, the $\Delta^{13}\text{C}$ results from few samples suggest the historic wood archives provide a reliable tree-ring carbon isotope record for tracking environmental changes of the last several centuries and may provide information about the timing of physiological changes in trees as a response to increasing atmospheric CO_2 concentrations.

Historic Log Buildings

Tree-ring dating of historic log buildings has a rich history in eastern North America. Dendroarchaeological methods have been used to provide inferred construction dates for numerous log buildings (e.g. Stahle, 1979; Lewis *et al.*, 2009; Slayton *et al.*, 2009; Garland *et al.* 2012; Schneider *et al.*, 2015), which then enhances historical interpretation of people, places, and events. Until recently, dendroarchaeological work in West Virginia was sparse. The first published report of historic log dating in the state (Cockrell *et al.*, 2017), conducted by the Montane Forest Dynamics Laboratory (myself included) at West Virginia University, was a foundational project that generated public interest in dendroarchaeology in West Virginia and provided me a network of hundreds of log building owners and agencies who were eager to learn the inferred construction date of their buildings. I quickly amassed a large collection of tree-ring data from ~30–40 log buildings and I continue to receive letters of interest from log building owners. This dissertation might not have been feasible if a rich history of dendroarchaeological dating in West Virginia had already been established and if the owners of these log buildings had not been willing to share them with me. By traveling to and sampling each building I was able to fully immerse myself in the forests I was reconstructing. Thus, the foundation of this dissertation was built upon happenstance, the generosity of others, and a lot of sawdust.

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Chapter 1: Historic log structures as ecological archives: A case study from eastern North America

Kristen K. de Graauw

Department of Geology and Geography, West Virginia University, Morgantown, WV 26505

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Abstract

Forests of eastern North America have undergone abrupt transformations over the last several centuries due to changing land use and climate. Researchers look to pre-settlement forests as a guide for forest restoration, though much of our understanding of composition and dynamics in pre-settlement forests is based on spatially restricted sediment records, few and fragmented old-growth stands in a narrow range of site types, and potentially biased historical documentation. Logs from historic structures hold information that may be useful to forest ecology in eastern North America, but before these records can be used, we must first establish where the logs originated, why they were selected over other trees, and what they can and cannot tell us about past forest ecology. Using a case study approach, I collected data from fifteen log structures in the central Appalachian region to compare construction site locations, species used, and mean diameter of logs through time to determine the ecological biases associated with human behavior in log structure construction.

Construction site locations changed from valleys to mountains through time and the species used in construction shifted from *Quercus alba* to a mix of *Quercus alba*, *Liriodendron tulipifera*, *Pinus strobus*, and *Castanea dentata* over time. The diameter of logs used in construction were generally consistent through time, with an average basal diameter of 31.3 cm (+/- 4.7). Mean age of logs increased through time for *Quercus* species, regardless of log diameter. These results suggest the species used for structural logs were selected by their abundance at the location of construction but that as construction site locations and resource availability changed through time, the species used in construction changed as well. While there are biases and limitations of dendroecological data from historic structures, the results presented here demonstrate that structural log data provide greater replication during the early European immigration period, representation of upland (valley) forest sites, and establishment of chronologies for species that are not well represented in current tree-ring chronologies (e.g. *Castanea dentata*, *Liriodendron tulipifera*). These results suggest structural logs can benefit ecological research by filling the temporal, spatial, and species void of tree-ring chronologies not only for the central Appalachian region, but also for other areas in eastern North America.

Keywords

dendroarchaeology; dendroecology; log structures; pre-settlement; eastern North America

Introduction

Forests of eastern North America have undergone major transformations over the last several centuries due to changing climate and land use. Managers and researchers look to pre-settlement forests as a guide for restoration in modern forests. Thus, it is important to understand forest composition and dynamics prior to extensive human impacts. Much of our understanding of pre-settlement forests is based on sediment records, old-growth forests, and historical documentation (Williams 1989, Abrams *et al.* 1995, Foster *et al.* 1996, Nowacki and Abrams 1997, Ruffner and Abrams 1998). While these paleo-environmental sources aid investigations of past processes and interactions between trees, forests, climate, and people (Berglund 2003, Wick *et al.* 2003, Marlon *et al.* 2008, Buntgen *et al.* 2011), each data source presents unique challenges.

Pollen and macrofossils from sediment cores provide long records about shifts in vegetation composition due to climatic and anthropogenic effects at watershed and regional levels (Webb 1981, Davis 1983, Delcourt and Delcourt 1997), but these records are spatially limited to areas with glacial lakes, bogs, and hollows, are taxonomically deficient, and are at best limited to decadal resolution. Tree rings provide annual records of forest disturbance but are often temporally limited by the fading record problem (Bowman 2007) which is particularly problematic in humid environments where wood decays rapidly. Further, remaining old-growth forests that provide relatively long records of forest change are spatially restricted to steep, often southwest facing, dry, and rocky slopes because of past logging and habitat restrictions of long-lived trees (Stahle and Chaney 1994, Therrell and Stahle 1998). Early land survey records and travelers' diaries provide accounts of forest composition, including tree density, dominant species, and disturbance events in pre-settlement forests. However, these contain biases such as misidentification of species, falsified information by surveyors, and preference for witness trees of particular species (Bourdo 1956, Black and Abrams 2001, Dyer 2001, Schulte and Mladenoff 2001, Bouldin 2008). When and where they are available, combinations of sediment, old-growth tree, and historical records can provide detailed evidence of past forest composition and dynamics (Spurr 1951, Howell and Kucera 1956, Webb 1981, Davis 1983, Loeb 1987, Mikan *et al.* 1994, Rentch and Hicks 2005, Wang 2007), but because these records are spatially and temporally limited, additional sources of pre-settlement forest composition and dynamics could improve ecological understanding in areas under-represented by paleo-environmental data.

The central Appalachian region is one such area in eastern North America that lacks spatially and temporally homogenous ecological data sources. This region is located within the largest contiguous area of temperate broadleaf trees in the world (Hicks 1998) and is part of the mixed mesophytic Appalachian oak forest, dominated by *Quercus* species such as *Quercus alba*, *Quercus rubra*, *Quercus velutina*, *Quercus coccinea*, and *Quercus montana* (Braun 1950, Dyer 2006). With 162 tree species, the mixed mesophytic forest is the most diverse of all forested regions in North America (Dyer 2006). *Quercus alba*, *Fagus grandifolia*, and to a lesser extent, *Pinus strobus* are found in upland valleys, while *Acer* species, *Fagus grandifolia*, *Tsuga canadensis*, *Prunus serotina*, *Quercus montana*, and *Picea rubens* dominate higher, drier, mountainous areas (Braun 1950, Thomas-Van Gundy and Nowacki 2013). Species such as *Liriodendron tulipifera*, *Tilia americana*, *Quercus rubra*, *Pinus strobus*, and *Fraxinus americana* are commonly found in the transitional areas between valleys and mountains. However, modern forests here may be significantly different from the pre-settlement forests that once covered the region, in both species composition and tree density (Abrams 2001, Abrams 2003, Rentch and

Hicks 2005, McEwan *et al.* 2011). Natural and anthropogenic events have altered forest species composition and density, disturbance regimes, and stand productivity throughout the region over the last several centuries (Stephenson 1986, Feng 1999, Brose *et al.* 2001, McEwan *et al.* 2011, Pederson *et al.* 2014a). Current tree-ring chronologies representing the central Appalachian region are both geographically skewed to the south and temporally restricted by a focus on just a few species that reliably reach great ages, making it difficult to study the effects of these changes. An additional data source would improve interpretations of forest change at both the local and regional scale.

Dendroclimatologists often use non-living sources of tree-ring data to study long-term climate variability, including wood from archaeological structures (Zhang *et al.* 2003, Cook *et al.* 2004, Buntgen *et al.* 2011), ancient dead wood in arid regions (LaMarche 1973, Grissino-Mayer 1996, Pederson *et al.* 2014b), and submerged subfossil wood (Stambaugh *et al.* 2011, Wilson *et al.* 2011). By combining living and dead sources, tree-ring chronologies have been extended by thousands of years, providing some of the longest tree-ring records of annually resolved climate variability in the world (LaMarche and Stockton 1974, Briffa 2000, Esper *et al.* 2002). While ancient dead wood and submerged subfossil wood are less abundant in eastern North America, there are countless sources of archaeological wood on the landscape in the form of historic log structures. Dendroarchaeological dating of log structures, though relatively new to eastern North America, has resulted in large collections of chronologies (e.g. Stahle 1979, Bortolot *et al.* 2001, Wight and Grissino-Mayer 2004, Grissino-Mayer and Van de Gevel 2007, Robichaud and Laroque 2008, Henderson *et al.* 2009, Querrec *et al.* 2009, Garland *et al.* 2012, Barclay and Rayburn 2014). As of yet, these collections have had little application outside of archaeological dating and extending chronologies for climate reconstructions (but see Pederson *et al.* 2014a).

Structural logs may hold ecological information useful to studies of forest ecology in eastern North America, including records of once prevalent species (e.g. *Castanea dentata*), and could cover a larger temporal and spatial domain than living old-growth trees alone. Further, the trees used for structural logs are unique in that many of them lived and died prior to the Industrial Revolution and contain information about tree growth that is unaffected by the increase in atmospheric CO₂ during the modern period. However, structural logs were likely selected from a forest population limited by the site of construction, the dominant species available at the construction site, and the size (diameter and height) and physiological characteristics of the available trees at that site. Before ecological information can be derived from historic structures, we must assess the potential biases associated with human behavior and why certain trees were chosen for construction.

During early European immigration in eastern North America people selected trees for log structures that were located on or near the construction site (Williams 1989, Rehder 2004). Construction sites were often on level terrain and near water sources (e.g. rivers, creeks, springs), as water was the most important resource required by early immigrants when choosing their home site (McRaven 1994, Caruso 2003, Rehder 2004). As populations grew, construction sites were located further from the early settlement nucleus and/or logs were extracted further from the construction site (Williams 1989, McRaven 1994). In the central Appalachian region, this often translated into migration from river valleys to higher elevations (Williams 2001, Caruso 2003). Logs of similar diameter were particularly important to build level structures (Mackie

1972). Many structures were constructed so that larger (or denser) logs were on lower levels and smaller logs were on higher levels. This technique was advantageous during a time with minimal construction technology. The most common species used for structural logs in eastern North America were *Quercus* species, though there were exceptions dependent upon the location of the structure and the dominant forest species in that area (Table 1). *Castanea dentata*, once found throughout the Appalachian region (Figure 1), was frequently used in construction as well (Wigginton 1972, McRaven 1994). Over time the availability of species for construction changed as resources were used (Rehder 2004). Human behavior greatly influenced the ecological information that is now archived in historic log structures.

Here I test three important assumptions about the reliability of ecological information in historic log structures using a group of fifteen structures from southeastern West Virginia. I ask the following questions: 1) What are the human behavior-related biases of log structure construction? 2) How will these biases limit or affect ecological information held within historic logs? 3) What types of ecological studies might historic logs serve? The goal of this case study is to carefully consider associated biases and limitations of structural log data and to provide a framework for further use of historic logs in ecological studies.

Study Area, History, and Materials

Southeastern West Virginia (Figure 2) is located at the convergence of the Appalachian Plateau, Allegheny Mountain, and Ridge and Valley physiographic provinces. Pre-settlement forests of West Virginia were estimated to cover 15.5 million acres, and by the early 1900's only 1.5 million acres of uncut forests remained (Brooks 1911). Modern forests of West Virginia are smaller, have different spatial coverage, and have lost dominant species and individuals due to pathogens and changing species composition (e.g. *Castanea dentata*, *Quercus alba*) (Braun 1950, Woods and Shanks 1959, Russell 1987, Abrams and McCay 1996, Abrams 2003, Rentch and Hicks 2005, McEwan *et al.* 2011). I selected this region for a case study because it provided a) numerous log structures from the early immigration period to the cessation of log built structures (approximately 1750 - 1900) that had not been previously tree-ring dated, b) a location that, while heavily forested during the early immigration period, has undergone extensive land management over the last 150 years, and c) a relatively under-represented region in tree-ring studies of pre-settlement forest composition and dynamics.

European immigration into present-day West Virginia began in the eastern regions as early as the late 1600s and progressed westward over time (Rice and Brown 2010). The earliest immigrants documented within the study area arrived around the 1740s (Brooks 1911, Dayton 1942). The counties containing the study area, from north to south, are Pendleton (founded in 1787), Pocahontas (founded in 1821), and Greenbrier (founded in 1777). During early European immigration log felling and shaping occurred using axes. By the 1770s, a few water mills existed in Pendleton county, and then between 1750 to 1780 few were operational in Greenbrier and Pocahontas counties (Brooks 1911). By the 1850s railroads were established in parts of the region, though the expansion of the rail line was gradual because of the topography of mountainous areas. Logging operations throughout the study area began in earnest around 1900 (Brooks 1911). Until logging operations were established, most land clearing was for agriculture and pasture and logs were either used to construct buildings or were burned for fuel. The succession of land use change over a relatively short amount of time makes this area a desirable location for a case study.

I inquired within local communities in southeastern West Virginia, by way of historical societies and county-level news sources, to locate historic log structures for this study. I documented and sampled a total of fifteen structures at fourteen sites (Table 2, Figure 2) to investigate the above research questions and examine the types and quality of ecological information that might be extracted from historic logs. The structures are owned mostly by private individuals, though some are maintained by historical societies (for examples of structures, see Figure 3). Structure owners presented to me any historical written and/or oral history suggesting a decade of construction, as documented in Table 2. I recorded the geographic and topographic location of each structure, and if it had been moved, the location of original construction (Table 2).

Dendroarchaeological Methods

All sampling procedures were as noninvasive as possible and were intended to reflect common dendroarchaeological sampling of historic structures in eastern North America (non-destructive, one core per log) so that ecological investigations can be replicated using past collections as well. At each structure selected for sampling, at minimum, two logs per wall per floor that displayed either bark or a complete, rounded outer edge to ensure samples represented felling dates for the structures. In larger structures, I selected four logs per wall per floor at maximum. I collected cores using an electric hammer drill with a hollow drill bit (14mm), coring on the underside of the log and reaching an estimated depth of log center to intercept pith. All holes were plugged using wood filler and corks to inhibit water and insect damage and to reinforce the cavity created by coring. I assigned a unique sample identifier to each core to reflect its location within the structure for determining overall felling dates. For example, sample MCE103A is from Mallow Church, East wall, 1st floor, 3rd log from bottom, first core (A). After collecting all cores, I measured the diameter of each cored log at both basal and distal ends, and at each sampling location on the log. I then sketched the walls of the structure, including number of logs present, sampling locations on logs, and diameter (cm) at each measured location. I mounted all cores on prefabricated wooden mounts using glue and clear tape, and sanded core surfaces with progressively finer sanding belts (100 to 400 ANSI-grit) to display ring boundaries and cellular structure (Orvis and Grissino-Mayer 2002). I used compressed air to remove sawdust from the sanded surface of cores for identification purposes. I then identified all cores to genus, and some to species, based on anatomical features (Hoadley 1990, Meier 2016).

I separated all cores at each site by genus for crossdating purposes. I assigned arbitrary years to the rings of each core, beginning with “1” at the innermost complete ring and counting outward to the outermost ring. At every decadal ring I marked one dot on the wood to facilitate measuring and internal crossdating of the cores prior to assigning calendar dates (Stokes and Smiley 1996). I then measured each ring-width on each core to the nearest 0.001mm using a sliding-stage Velmex micrometer (Velmex Inc, Bloomfield, New York) and program Tellervo (Brewer *et al.* 2011). I used COFECHA (Dendrochronology Program Library (DPL) (<http://www.ltrr.arizona.edu/pub/dpl/>)) to statistically crossdate the undated tree-ring series and verified internal crossdating visually (Grissino-Mayer 2001). Correlation coefficients were calculated for 40-year segments with 20-year overlaps for each series. When series had less than 50 rings on average I used 20-year segments with 10-year overlaps. After I verified internal crossdating statistically and visually, I then externally crossdated the undated series against local and regional tree-ring chronologies from the International Tree Ring Data Bank (ITRDB) and other collections (Table 3). I selected these reference chronologies based on species, proximity to

the structures, similar topography, and chronology length. For each structure, I compared multiple reference chronologies with the undated series in COFECHA to assign calendar dates. I assigned calendar dates to undated series if multiple segments had the same, or similar, recommended dating adjustments across reference chronologies. I used the program ARSTAN (DPL) to detrend each absolutely-dated series using a negative exponential curve to remove age-related growth trends. I then retested each standard chronology against the regional chronologies in COFECHA to obtain correlation coefficients. Site chronologies that were highly correlated with the same regional reference chronologies were then grouped together to create local chronologies, which were then graphically compared with the corresponding reference chronology. Once the series were absolutely dated, I inspected the outermost ring of each sample to evaluate terminal ring attributes and determine felling years, using standard codification from Bannister (1962) and Nash (1999) and used elsewhere (Mann *et al.* 2009, Grissino-Mayer *et al.* 2012, de Graauw *et al.* 2014).

Descriptive Analyses

Based on tree-ring felling dates, I binned structures into three phases of construction for comparative analyses: 1750-1799; 1800-1849; and 1850-1899. To address changes in construction site locations over time, I categorized structure locations into valleys and mountains, and then further into major and minor valleys and major and minor mountains, based on field observations and satellite/aerial imagery, and compared results over time. For sites with multiple structures or phases of construction only the original construction dates were used for analysis, leaving a total of 14 structure sites for comparison of site types. I binned all species from each structure by site category (major valley, minor valley, major mountain, and minor mountain) to address how species selected for construction changed with the geographic location of structures. I then compared the presence of each species by decade of construction. To investigate the average diameter of logs used at each site I calculated the mean basal end diameter and standard deviation of all sampled logs at each site and the overall average diameter by species.

Dendroarchaeological Results

In total, 305 cores were crossdated and 23 site chronologies were created (Table 4). Logs were felled for the oldest structure in 1786 and in 1880 for the youngest structure. Four species were represented across the structures: *Quercus alba*, *Pinus strobus*, *Liriodendron tulipifera*, and *Castanea dentata*. All identified species are within their modern ranges (Figure 1). It is difficult to differentiate between some species in the white oak group (e.g. *Quercus alba*, *Quercus stellata*, and *Quercus montana*) based on anatomical features within the cross-sectional surface of a core and without bark and leaf shape for reference, but *Quercus alba* was most often used historically because of its physiological characteristics (Meier 2016) and wide range (Figure 1) (USDA 2017). For example, *Quercus stellata* cannot be distinguished from *Quercus alba* at the cellular level. *Quercus stellata* is classified as an upland species for the Eastern Mountains and Piedmont Region (USDA 2017) so it is possible it was used for construction in higher elevations of this region as well. However, it is inferior to *Quercus alba* in lumber quality (Meier 2016). *Quercus montana*, another potential white oak selected for construction, lacks tyloses in its pores (like *Quercus rubra*), and therefore can be easily distinguished from other species in the white oak group (Meier 2016). It is often not as straight-growing as other white oak species and may

not have been favorable for construction for this reason as well. I assume all samples are *Quercus alba*, though it is possible other white oak species are present in the data.

Internal crossdating at most sites yielded moderately to highly correlated series (> 0.400) (Table 4). However, three of the chronologies had correlations that fell below 0.400; two *Castanea dentata* sites (PBC and FCC) and one *Quercus alba* site (KMQ). The low correlations of *Castanea dentata* series are likely due to low sensitivity and shorter time series, whereas the low correlations of the *Quercus alba* site chronology KMQ (two series) are likely due to lack of replication. External crossdating at many sites was strong, though seven of the chronologies had correlations with their most-correlated reference chronologies that fell below 0.400. These low correlations may be a factor of species longevity, sensitivity, and spatial relation to the reference chronologies, as there are few reference chronologies nearby to the study area or within the same physiographic province. For all but *Quercus alba*, there were few regional reference chronologies for comparison, yielding low correlations. *Castanea dentata*, for example, with less than 100 rings on average, was crossdated against *Quercus alba* regional chronologies with greater sensitivity, so lower correlations were anticipated. Graphical comparisons between site chronologies and reference chronologies for *Quercus alba* (Figure 4), *Castanea dentata* (Figure 5), *Liriodendron tulipifera* (Figure 6), and *Pinus strobus* (Figure 7) demonstrate varying strength of signal for the different species as indicated by frequency and strength of marker years.

All structures had conclusive felling dates based on terminal ring attributes (Table 5). Felling dates (denoted by B or r) were concurrent for all structures with multiple species, excluding structures for which additions had been made. No replacement logs were identified in any of the structures. However, two structures (the Barracks and Caraway House) had multiple phases of construction as additions were made to the original structures. All structures with two consecutive felling dates had logs which were felled in both the late growing season of the previous year and pre-or-early growing season of the following year (e.g. late 1818 and early 1819).

Descriptive Results

Of fourteen total structure sites (Table 2), seven were located in valleys and seven on mountains. Valley sites decreased as mountain sites increased through time (Figure 8). There were more major valley sites (6) than minor valley sites (1) and more minor mountain sites (4) than major mountain sites (3) (Figure 9). Four species (*Quercus alba*, *Pinus strobus*, *Liriodendron tulipifera*, and *Castanea dentata*) were present in structures in this study, but their abundance shifted through time and across site types. Through time, species in structures shifted from dominantly *Quercus alba* to a mix of *Liriodendron tulipifera*, *Quercus alba*, *Castanea dentata*, and *Pinus strobus* (Figure 10). *Quercus alba* was most abundant during the periods 1750-1799 and 1800-1849 and *Liriodendron tulipifera* was most abundant during the period 1850-1899. The species present in structures varied by site type (Table 6), but *Quercus alba* was the most abundant species across all site types (38.1% of total species present). In major valley sites *Quercus alba* was most abundant, in minor valley sites *Pinus strobus* was the only species present, in minor mountain sites *Quercus alba* and *Liriodendron tulipifera* were equally abundant, and in major mountain sites *Castanea dentata* was most abundant (Table 6). Across all logs the average basal end diameter was 31.3 cm (± 4.7 cm) and mean log diameters differed only slightly by species (>10 cm) (Table 7). By species the average basal diameter was

28.5 cm for *Quercus alba*, 33.5 cm for *Pinus strobus*, 34.5 cm for *Castanea dentata*, and 35.8 cm for *Liriodendron tulipifera*. Only *Quercus alba* had enough site replication for meaningful analysis of diameter and ring width relationships. Average log diameter varied slightly for *Quercus alba*, with no significant relationship to time ($R^2 = 0.0144$) (Figure 11). Likewise, average log diameter had no significant relationship with tree age (number of rings present ($R^2 = 0.0873$)), though the subtle trend was towards greater diameter with increased age (Figure 11). Average ages at the time of felling increased through time ($R^2 = 0.4657$), with the most recently felled logs (and oldest in age) being from valley sites (Figure 11). The outlier with age of 138 years and felling date of 1794 is Mallow Church, constructed on a minor mountain site. Average ring width decreased through time ($R^2 = 0.4739$), and as expected, is roughly inverse to the relationship between age and time (Figure 11).

Interpretation and Discussion

This study demonstrates there are biases associated with human behavior including geographic immigration patterns, preferred species for construction, and desired log size for structural walls. Depending on the period of construction and immigration patterns in an area, certain forest types and species will be dominant over others in structural log data. Analysis of the fifteen structures in the central Appalachian region demonstrates movement from valley to mountain sites over time and a shift in species from predominantly *Quercus alba* during the early period to a mix of species, dominated by *Liriodendron tulipifera*, during the later period (Figures 8, 9, 10). Dominant species used in construction appear to be strongly tied to site locations, suggesting the species used for structural logs varied by location and were likely determined foremost by abundance in the surrounding forest. As construction site locations and resource availability changed through time, the species available for use changed as well. In this study *Quercus alba* was the most dominant species, though its abundance fluctuated through time and by site type. The use of other species instead of *Quercus alba* during the later period (Figure 10) might be representative of overuse of this species during the early period, and a transition to less desirable species for construction. A temporal shift in species used for construction was documented in New York as well, and it was suggested this was likely due to over-exploitation of the diameter class of selected species over time (Barclay and Rayburn 2014). Conversely, it could simply represent migration to more remote areas where available species differ from those found in upland valleys. The species present in this study (excluding *Castanea dentata*) are consistent with those used in other dendroarchaeological studies in eastern North America (Table 1), which suggests species were likely selected for log structures based on their relative abundance (dominance) in forests and from a pool of preferred species. The absence of *Castanea dentata* from dendroarchaeological literature in eastern North America (Table 1) is likely due to challenges of crossdating structural logs, such as ring-width complacency, inadequate number of rings, and few reference chronologies.

Most structures sampled here showed little difference in basal end diameters, but there were a few structures with significant differences in mean basal diameters within the structure (Table 7). This disparity in mean basal diameters within a structure could reflect construction techniques of that time (larger, denser logs at ground level). Mean basal diameters of structural logs differed by species, suggesting a particular (“ideal”) diameter was not as important for construction as the availability of trees with similar diameter at construction sites. Not all diameter classes of trees available in an area were represented in a log structure. However, the presence of these logs in a

structure suggests the represented diameter classes were abundant in the forests surrounding the construction site, as many trees were needed to build each structure. Further, because there was no indication of an “ideal” diameter used in construction, multiple diameter classes were used over time and across site types (and associated species). More importantly, because many species can undergo long periods of growth suppression, similar size does not always indicate similar age. It is possible to recover a range, and perhaps representation, of local forest age structure, excluding small trees. For example, *Quercus alba* showed no meaningful difference in diameter through time, though average age increased (Figure 11). Though log diameter was controlled by those who built the structures, ecological information obtained from logs describes various age classes within pre-settlement and early-settlement forests. No structures from the earliest period of European immigration in this region were located, though early logging and land use practices of this region may be reflected in the increasing age and varying diameters of trees through time as pre-settlement trees matured, were used for construction, and new cohorts of trees matured and were harvested during the 1800s.

Based on the results and biases above, there are a few limitations of log structure data that must be assessed before conducting an ecological study. 1) Forest species composition and diameter classes are not fully represented in logs and therefore, studies of complete forest dynamics are not possible to conduct using structural logs alone. However, most structural logs indicate one or few of the dominant forest species and diameter classes at a given time. 2) Sites near major water sources (valley sites here) will be represented far more than sites near minor water sources (mountain sites here) during early immigration into an area. This relationship between site type and period of construction will greatly influence which species are represented in structures. The dominant species represented at each site type in this study are also dominant in corresponding modern forests of this region. 3) Some species and time periods could be absent from the historic structure record because of the loss of historic structures over time. For example, I was unable to locate any structures that were constructed earlier than 1786, though early European immigration to this region began around 1750. Additionally, I saw no indications of log reuse in any structures. Written history suggests many early log structures were destroyed during times of conflict (Dayton 1942, Caruso 2003, Barclay and Rayburn 2014), deteriorated naturally (McRaven 1994), or were used for parts elsewhere (Rehder 2004). Absence of a species from the historic structure record could promote false interpretations of available species at a site or time, similar to issues with pollen records. White pine, for example, may be absent from the early period in this study because of decay, arson, or reuse.

Keeping in mind the biases and limitations of these data, there is still an assortment of ecological information that can be extracted from historic timbers. The information held within structural logs fills temporal, spatial, and species gaps in tree-ring chronologies not only for the central Appalachian region, but also for other areas in eastern North America where tree-ring records are sparse. Ecological studies conducted using tree rings from log structures achieve greater replication during the early European immigration period, representation of upland (valley) forest sites, and establishment of chronologies for species that are not well represented in current tree-ring chronologies (e.g. *Castanea dentata*, *Liriodendron tulipifera*). Of these benefits, perhaps the greatest contribution of structural log data to forest ecology is the representation of valley trees, as they are predominantly characteristic of a different site type than current old-growth forests. Areas of potential research using log structure data include 1) substantiation of

land survey records for dominant species composition during the pre-settlement period, 2) investigations of disturbance history during the pre-and-early-settlement periods, including land use/logging effects on dominant species canopy succession, and 3) examination of pre-industrialization growth and water-use efficiency of trees uninfluenced by increasing atmospheric CO₂. There are doubtlessly more ways in which structural log data might be used in forest ecology than have been considered here (see Trouet *et al.*, in review, for further discussion). The applications suggested above are a few examples of what might be accomplished using data contained within historic logs.

Conclusions

Researchers and forest managers seek to better understand the ecological repercussions of abrupt forest changes, particularly those that occurred during the pre-and-early-settlement periods, but records of past forests with annual resolution are limited because of extensive logging and land clearing in the 20th century. Much of our understanding of forest structure and dynamics prior to European immigration is based on few old-growth forests that are spatially restricted by rugged terrain and harsh growing conditions not representative of typical pre-settlement forests. Logs from historic structures contain annual tree-ring records of past forest ecology, but before these records can be used in a meaningful way, we must first establish where these logs originated, why they were selected over other trees in the forests, and what they can and cannot tell us about past forest ecology. Because certain sites, species, and individual trees were selected for log structures (not at random), ecological biases are inherent in the data. In this study, I have examined the biases and limitations of structural log data and suggested possible applications in ecological studies with careful consideration. Tree-ring data from structural logs could supplement our understanding of past forests in eastern North America by providing greater species diversity, spatial extent, and temporal depth to forest ecology studies. Many tree-ring laboratories have collections of log structure data, and some have access to structures older than those documented here. With little to no additional field work these collections could be used to build a collective network of forest ecology reconstructions from historic logs, furthering our understanding of pre-settlement forests and better informing future management decisions.

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Table 1. Species documented in dendroarchaeology studies throughout eastern North America by forest region, as defined in Dyer 2006, and ordered from northernmost to southernmost location.

Species (in order of abundance)	State/ Province	Forest Region*	Citation
<i>Thuja occidentalis</i>	Quebec	Boreal	Querrec <i>et al.</i> 2009
<i>Picea rubens</i>	Nova Scotia	Northern Hardwoods- Hemlock	Robichaud and Laroque 2008
<i>Pinus, Tsuga, Quercus, Fraxinus, Picea, Betula, Acer, Ulmus, Prunus, Thuja, Carya</i>	New York	Northern Hardwoods- Hemlock	Barclay and Rayburn 2014
<i>Quercus alba</i>	West Virginia	Mesophytic – Appalachian oak	de Graauw (<i>unpublished</i>)
<i>Fagus, Liriodendron tulipifera, Quercus alba, Acer</i>	Kentucky	Beech-Maple- Basswood	Baas and Rubino 2014
<i>Quercus alba, Liriodendron tulipifera, Robinia pseudoacacia</i>	West Virginia	Mesophytic – Appalachian oak	Cockrell <i>et al.</i> 2017, in press
<i>Quercus alba</i>	Virginia	Mesophytic – Appalachian oak	Grissino-Mayer <i>et al.</i> 2012
<i>Quercus alba</i>	Virginia	Mesophytic – Appalachian oak	Bortolot <i>et al.</i> 2001
<i>Quercus alba</i>	Tennessee	Mesophytic – Appalachian oak	Grissino-Mayer and van de Gevel 2007
<i>Quercus</i>	Tennessee	Mesophytic – Appalachian oak	Mann <i>et al.</i> 2009
<i>Juniperus virginiana</i>	Tennessee	Mesophytic/ Beech-Maple- Basswood	Lewis <i>et al.</i> 2009
<i>Quercus alba, Pinus</i>	Tennessee	Mesophytic	Slayton <i>et al.</i> 2009
<i>Quercus alba</i>	Tennessee	Mesophytic	Stachowiak <i>et al.</i> 2014
<i>Juniperus virginiana</i>	Tennessee	Mesophytic/ Beech-Maple- Basswood	Schneider <i>et al.</i> 2015
<i>Quercus alba, Liriodendron tulipifera</i>	North Carolina	Mesophytic	Henderson <i>et al.</i> 2009
<i>Pinus echinata</i>	Georgia	Southern Mixed – Oak-Pine	Wight and Grissino- Mayer 2004
<i>Pinus palustris</i>	Florida	Subtropical Evergreen	Grissino-Mayer <i>et al.</i> 2010

Table 2. Fifteen structures (14 sites) from across southeastern West Virginia were used in this study. The historical construction date, based on written and/or oral history is rounded to the decade. The species sampled were QUAL = *Quercus alba*; PIST = *Pinus strobus*; LITU = *Liriodendron tulipifera*; and CADE = *Castanea dentata*. They are listed by order of abundance within the structure. Site type (MAV = major valley, MIV = minor valley, MAM = major mountain, MIM = minor mountain), and location coordinates are for the original location of each structure or complex of structures, as some have been relocated. Documented locations of structures are approximate to maintain anonymity of owners.

Structure	Site Type	Historical Date	Location (Decimal°)
Diamond Barn	MAV	1770	38.15, -80.20
Caraway House	MIM	1770	38.04, -80.30
Caraway Barn		1770	
Barracks	MAV	1780	37.80, -80.44
Mallow Church	MIM	1790	38.77, -79.26
Jarrett House	MAV	1810	37.77, -80.63
Kile Homestead	MAV	1810	38.77, -79.28
Keeney Cabin	MAV	1820	37.76, -80.61
Herold Barn	MIV	1830	38.14, -79.99
Kee (cabin) Museum	MIM	1830	38.20, -80.11
Pitsenbarger Barn	MAM	1840	38.58, -79.30
Sisler Cabin	MIM	1840	38.07, -80.29
Fish Camp Cabin	MAM	1850	38.32, -80.10
Zigafuss House	MAV	1860	37.91, -80.62
Little House	MAM	1870	38.07, -80.33

Table 3. Reference chronologies from the International Tree Ring Data Bank and private collections used to assign calendar dates to structural logs. Species: QUAL = *Quercus alba*; LITU = *Liriodendron tulipifera*; PISP = *Pinus* spp.; PIST = *Pinus strobus*.

Reference Chronology	Species	Span	Max Replication	State	Latitude	Longitude	Citation
CFQ	QUAL	1670-2013	24	WV	38.21	-80.94	Cockrell <i>et al.</i> (this issue)
VA011	QUAL	1552-1983	26	VA	37.38	-80.50	Cook 1983
VA017	QUAL	1569-1982	23	VA	37.92	-79.80	Cook 1982
KY003	QUAL	1660-1982	40	KY	37.08	-83.00	Cook 1982
FGT	LITU	1668-2002	40	KY	37.89	-85.93	Maxwell <i>et al.</i> 2011
TN016	LITU	1736-1995	22	TN	35.60	-83.08	Young <i>et al.</i> 1995
KY006	PISP	1750-2004	42	KY	37.88	-83.68	Guyette <i>et al.</i> 2012
PA008	PIST	1679-1981	24	PA	41.33	-79.20	Cook 1981

Table 4. Dating results from fourteen sites. All species in a structure were separated for crossdating and given dating IDs. Not all collected cores were dated. Dating Interval shows total range of dated rings from a structure. Series intercorrelation (Series IC) was calculated in COFECHA. “n rings” is the average number of rings represented across series at a site. The highest reference chronology (Ref CRN) correlations are reported.

Structure	ID	Species	Cores	Dated Cores	Dated Interval	Series IC	n Rings	Ref CRN	Correlation
Diamond Barn	DBQ	QUAL	30	23	1684-1786	0.668	77	CFQ	0.498
Jarrett House	JHQ	QUAL	15	15	1674-1793	0.621	100	CFQ	0.595
Mallow Church	MCQ	QUAL	16	15	1586-1794	0.539	138	KY003	0.505
Caraway House	CYQ	QUAL	12	10	1680-1795	0.545	84	CFQ	0.596
Barracks	BAR1	QUAL	33	32	1683-1799	0.681	79	CFQ	0.448
Caraway Addition 1	Q CY1Q	QUAL	15	14	1685-1804	0.557	91	CFQ	0.535
Caraway Barn	CBQ	QUAL	28	17	1682-1824	0.566	115	CFQ	0.463
Keeney Cabin	KCQ	QUAL	21	12	1699-1829	0.536	88	CFQ	0.531
Kile Homestead	KHQ	QUAL	22	21	1691-1833	0.536	102	VA017	0.443
Herold Barn	HBP	PIST	21	11	1709-1836	0.592	80	KY006	0.311
Pitsenbarger Barn	PBQ	QUAL	22	21	1706-1840	0.512	93	VA017	0.417
	PBC	CADE	7	7	1764-1840	0.338	43	VA017	0.362
Little House	LHC	CADE	16	16	1815-1863	0.643	40	KY003	0.505
Kee (cabin)	KML	LITU	20	19	1777-1865	0.601	62	FGT	0.378
Museum	KMQ	QUAL	2	2	1708-1865	0.350	152	CFQ	0.522
Sisler Cabin	SCL	LITU	23	17	1719-1869	0.530	74	TN016	0.465
Zigafuss House	ZHQ	QUAL	19	19	1675-1874	0.662	152	CFQ	0.601
	ZHL	LITU	3	3	1820-1874	0.484	66	FGT	0.208
Fish Camp Cabin	FCL	LITU	13	5	1657-1876	0.430	176	TN016	0.313
	FCP	PIST	4	4	1641-1876	0.513	132	PA008	0.229
	FCC	CADE	2	2	1787-1876	0.209	83	VA011	0.223
Barracks Addition 1	BAR2 Q	QUAL	15	15	1698-1877	0.592	132	CFQ	0.578

Caraway Addition 2	CY2L	LITU	6	5	1796-1880	0.549	76	FGT	0.485

Table 5. Felling dates and terminal ring attributes (TRA) from fifteen structures. TRAs are percent totals of all cored logs at the site and are categorized by B = terminal ring present with bark; r = terminal ring present, no bark; v = sapwood present, terminal ring absent; vv = no sapwood present, terminal ring absent; ++ = break in core, ring count to terminal ring required (modified from Bannister 1962 and Nash 1999).

Structure	Species	Felling Date(s)	Dated Cores	B/r	v	vv	++
Diamond Barn	QUAL	1786	23	100	---	---	---
Jarrett House	QUAL	1792/1793	15	53.3	13. 3	---	33. 3
Mallow Church	QUAL	1794	15	73.3	26. 7	---	---
Caraway House	QUAL	1794/1795	10	90	10	---	---
Barracks	QUAL	1799	32	65.6	12. 5	18. 8	3.1
Caraway Addition 1	QUAL	1803/1804	14	100	---	---	---
Caraway Barn	QUAL	1824	17	76.5	23. 5	---	---
Keeney Cabin	QUAL	1829	12	16.7	58. 3	25	---
Kile Homestead	QUAL	1831-1833	21	76.2	9.5	---	14. 3
Herold Barn	PIST	1835/1836	11	36.4	---	---	63. 6
Pitsenbarger Barn	QUAL	1839/1840	21	90.5	---	9.5	---
	CADE	1839/1840	7	57.1	42. 9	---	---
Little House	CADE	1863	16	81.3	18. 8	---	---
Kee (cabin) Museum	LITU	1865	19	73.7	21. 1	---	5.3
	QUAL		2	50	50	---	---
Sisler Cabin	LITU	1869	17	94.1	5.9	---	---
Zigafuss House	QUAL	1874	19	52.6	21. 1	15. 8	10. 5
	LITU		3	100	---	---	---
Fish Camp Cabin	LITU	1876	5	100	---	---	---
	PIST		4	75	25	---	---
	CADE		2	100	---	---	---
Barracks Addition 1	QUAL	1877	15	33.3	33. 3	20	13. 3
Caraway Addition 2	LITU	1880	5	60	40	---	---

Table 6. Percentage of all species present in structures (and count) by site type, ordered from greatest to least total presence. QUAL (*Quercus alba*) had the greatest representation across all sites (38.1%) and was most abundant in major valleys. PIST (*Pinus strobus*) was most abundant in minor valley sites. LITU (*Liriodendron tulipifera*) was most abundant in minor mountain sites and CADE (*Castanea dentata*) was only present on major mountain sites. Number of sites included in each percentage are in parentheses.

Site Type	QUAL (%)	PIST (%)	LITU (%)	CADE (%)
Major Valley	85.7 (6)	0	14.3 (1)	0
Minor Valley	0	100 (1)	0	0
Major Mountain	16.7 (1)	16.7 (1)	16.7 (1)	50 (3)
Minor Mountain	50 (3)	0	50 (3)	0
Total % Presence	38.1	29.2	20.2	12.5

Table 7. Average basal end diameters by site, with standard deviations (SD), and by species from all sites. N logs is number of logs measured from sampled logs. Some sampled logs could not be measured because of structural obstructions, so n logs measured is equal to or less than n logs sampled.

Structure	ID	n logs	Avg. Basal Diam. (cm)	SD	Species	Total Avg. Diam.(cm)
Diamond Barn	DBQ	22	30.8	2.3	QUAL	28.5
Jarrett House	JHQ	14	21.5	1.6		
Mallow Church	MCQ	15	33.8	3.3		
Caraway House	CYQ	8	23.8	2.9		
Barracks	BAR1Q	20	29.1	5.6		
Caraway Addition 1	CY1Q	14	25.0	2.3		
Caraway Barn	CBQ	12	31.5	3.7		
Keeney Cabin	KCQ	7	32.1	3.0		
Kile Homestead	KHQ	9	34.4	2.5		
Pitsenbarger Barn	PBQ	21	21.9	2.5		
Kee (cabin) Museum	KMQ	2	28.6	4.3	CADE	34.5
Zigafuss House	ZHQ	17	32.2	3.9		
Barracks Addition 1	BAR2Q	9	26.3	4.8		
Pitsenbarger Barn	PBC	7	23.8	5.3		
Little House	LHC	16	31.0	3.2		
Fish Camp Cabin	FCC	2	48.7	18.3	LITU	35.8
Kee (cabin) Museum	KML	17	28.5	5.2		
Sisler Cabin	SCL	16	31.1	6.0		
Zigafuss House	ZHL	3	31.4	4.1		
Fish Camp Cabin	FCL	5	50.5	11.5	PIST	33.5
Caraway Addition 2	CY2L	4	37.5	3.4		
Fish Camp Cabin	FCP	4	29.7	7.0		
Herold Barn	HBP	9	37.3	2.5		
Total Avg. Basal Diameter						31.3

Figure 1. Species distribution maps (dark grey) centered over the central Appalachian region, including the study area in West Virginia, for A) *Quercus alba*; B) *Castanea dentata*; C) *Quercus stellata*; D) *Pinus strobus*; E) *Liriodendron tulipifera*. *Quercus alba*, *Castanea dentata*, and *Liriodendron tulipifera* ranges encompass all of West Virginia. *Quercus stellata* is found throughout the state, excluding the most northern reaches and *Pinus strobus* is found in the eastern mountains and parts of northern and western West Virginia. Shapefiles acquired from USGS GEC (<https://gec.cr.usgs.gov/data/little/>).

Figure 2. Locations of fourteen sites (fifteen structures) sampled for this study in West Virginia, at the intersection of the Appalachian Plateau (southwest), Allegheny Mountain (northwest) and Ridge and Valley (east) physiographic provinces of the central Appalachian region of the eastern U.S.

Figure 3. Examples of structures used in this study and representing different periods of construction from 1786 to 1880. A) The Barracks, *Quercus alba*, 1799; B) Kee (cabin) Museum, *Liriodendron tulipifera* and *Quercus alba*, 1865; C) Pitsenbarger Barn, *Quercus alba* and *Castanea dentata*, 1840; D) Zigafuss House, *Quercus alba* and *Liriodendron tulipifera*, 1874. Photos: K. de Graauw.

Figure 4. Graphical comparison of *Quercus alba* reference chronology, CFQ, with chronology of *Quercus alba* series from structures in the Appalachian Plateau (APQ) and Ridge and Valley (RVQ). Structures included in APQ are DBQ, JHQ, CYQ, BAR1Q, CY1Q, CBQ, KCQ, KMQ, ZHQ, and BAR2Q. Structures included in RVQ are MCQ, PBQ, and KHQ. Vertical grey lines are included to highlight some of the concurrent marker years.

Figure 5. Graphical comparison of *Quercus alba* reference chronology, VA017, with *Castanea dentata* structure chronologies LHC, FCC, and PBC. *Quercus alba* structure chronology PBQ, from the same structure as PBC, is included for comparison as well. Vertical grey lines are included to highlight some of the concurrent marker years.

Figure 6. Graphical comparison of *Liriodendron tulipifera* reference chronology, FGT, with *Liriodendron tulipifera* structure chronologies SCL, KML, CY2L and ZHL. Vertical grey lines are included to highlight some of the concurrent marker years.

Figure 7. Graphical comparison of *Pinus strobus* reference chronologies, KY006 and PA008, with *Pinus strobus* structure chronologies FCP and HBP. Vertical grey lines are included to highlight some of the concurrent marker years.

Figure 8. Comparison of structure locations through time, seven valley sites (light grey) and seven mountain sites (dark grey), from 1780 to 1876. Structure sites in valleys are more abundant during the early period, but after 1840 there is a shift to more mountain site locations, which suggests the temporal distribution of structure locations represents expected migration and land-use patterns.

Figure 9. Comparison of structure locations in major valley, minor valley, major mountain, and minor mountain sites by time periods 1750-1799, 1800-1849, and 1850-1899. Major valley sites decreased through time and both mountain sites increased during the late period.

Figure 10. Dominant species present in structures by 50-year period. QUAL = *Quercus alba*; PIST = *Pinus strobus*; LITU = *Liriodendron tulipifera*; CADE = *Castanea dentata*. QUAL is dominant until the period 1850-1899, at which point LITU becomes the most dominant species. Species diversity in structures is highest during the period 1850-1899 and lowest during the period 1750-1799.

Quercus alba

Figure 11. Analysis of *Quercus alba* average basal end log diameter (in cm) by felling date (A), average basal end log diameter (in cm) by average log age (number of rings present) (B), average log age (number of rings present) by felling date (C), and average ring width of logs by felling dates (D).

Chapter 2: Do historic log buildings provide evidence of reforestation following depopulation of Indigenous Peoples?

Kristen K. de Graauw*, Amy E. Hessel*

*Department of Geology and Geography, West Virginia University, Morgantown, WV 26505

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ABSTRACT

Aim: To test the previously published hypothesis that there was widespread reforestation following the depopulation of Indigenous Peoples in the 16th and 17th centuries.

Location: The central Appalachian Mountains of eastern North America.

Methods: To test for reforestation following depopulation, we used tree-ring evidence of tree recruitment, early radial growth, and growth releases from 18 historic log buildings ($n = 361$ logs) and 8 old-growth forest sites ($n = 197$ trees). We used inner-ring dates to determine if a synchronous recruitment event(s) was present at historic sites but absent from old-growth sites following depopulation. We used cluster analysis to determine if historic logs established in a clearing (fast early growth) or under a canopy (slow early growth). Similarly, we calculated disturbance rates (growth releases per 100 years) to determine if historic logs grew in a clearing (low disturbance) or under a canopy (high disturbance).

Results: Historic log and old-growth forest sites both document a period of elevated recruitment beginning in the 1670s. This event was observed in previous studies and across site types, suggesting that either climate variability or the absence of low-intensity land use (e.g. fire) may have also contributed to forest establishment. Most historic sites (61%–83%) had fast early growth, indicating growth of trees in high-light conditions. The rate of disturbance was lower at historic sites with fast early growth (5.3 events/century, 95% CI [3.6, 7.0]) than at old-growth sites with slow early growth (23.5 events/century, 95% CI [17.5, 29.5]), consistent with the idea that most historic logs were harvested from fast-growing, second-growth forests that established after depopulation.

Main Conclusions: Our results support the hypothesis of reforestation in upland forests of the central Appalachian Mountains following depopulation and suggest that upland forests, at the time of European immigration, were at least in part, a legacy of indigenous land-use practices. However, the timing of a regional drought event, depopulation, and subsequent recruitment of trees, all within the period of ~1650–1690 CE, warrants further research into interactions between indigenous land use and climate during a pivotal period in North American history.

Keywords: abandonment, disturbance, forest regrowth, land use, Native American, radial growth, recruitment, succession, tree ring

INTRODUCTION

The relative magnitude of forest management in the Americas prior to European immigration has long been a subject of debate (Denevan, 1992; Doolittle, 1992; Vale, 2002; Marlon et al., 2008). While 19th century accounts suggested that land-use impacts of Indigenous Peoples were minimal, with only locally concentrated disturbances occurring until the arrival of European immigrants (Bakeless, 1950; Shetler, 1991), other sources (Denevan, 1992; Doolittle, 1992) support a more widespread impact of indigenous land use on forest structure and composition. Historical sources and sediment records indicate that Indigenous Peoples practiced a variety of land management techniques, including high-intensity activities (e.g. logging) and low-intensity forest management (e.g. understory burning) (Williams, 1989; Denevan, 1992; Doolittle, 1992; Delcourt & Delcourt, 1997; Lafon et al., 2017). Recently, it has been proposed that forest regrowth following land abandonment may have been widespread enough to explain the drawdown in global CO₂ and associated cooling observed during the coldest part of the Little Ice Age (~1570–1650 CE) (hereafter: ‘extensive forest regrowth model’) (Dull et al., 2010; Nevle et al., 2011; Lewis & Maslin, 2015; Koch et al., 2019). Evaluating the degree of forest establishment after depopulation of Indigenous Peoples requires careful investigation of the forest history of the Americas and has the potential to alter our fundamental understanding of forest structure and dynamics prior to European contact.

Paleoecological archives, such as tree-ring records, should record the response of forests to land-use change of this magnitude, for example through tree recruitment following land abandonment (Liebmann et al., 2016) or through growth anomalies in establishing and extant trees (McEwan & McCarthy, 2008). Tree rings have been widely used to investigate the effects of forest disturbances, for example through pulses of tree recruitment following secondary succession (Foster, 1988) and rapid changes in growth initiated by canopy gaps (Runkle & Yetter, 1987; Lorimer & Frelich, 1989). However, much of our understanding of forest composition and dynamics in eastern North America prior to European immigration is based on tree-ring data from few, fragmented, and spatially restricted old-growth forests (Abrams et al., 1995; Foster et al., 1996; Nowacki & Abrams, 1997). Due to deforestation since European arrival, many extant old-growth forests are restricted to dry, rocky, southwest-facing slopes (Therrell & Stahle, 1998) that were less suitable for human occupation, and are therefore not ideally located to record land-use prior to or following depopulation of Indigenous Peoples.

Log buildings, constructed in upland valleys at the time of European immigration, represent a different forest type than remnant old-growth forests (de Graauw, 2017). European immigrants sought flat, fertile land near water for agriculture and pasture, and with ample, straight timber on site for construction of their houses, barns, and outbuildings (Kercheval, 1902; Williams, 1989). These are the same characteristics that describe sites occupied by Indigenous Peoples prehistorically (Kercheval, 1902; McWhorter, 1915; Gardner, 1983; Williams, 1989; Potter, 1993; Coughlan & Nelson, 2018). Thus, indigenous land-use legacies might be stored in the timbers of historic log buildings.

We propose that if upland forests experienced massive recruitment of trees on land abandoned by Indigenous Peoples, tree rings from historic logs should capture those land-use changes through evidence of: 1) synchronous recruitment dates; 2) early radial growth patterns; and 3) growth release events. Synchronous recruitment events, identified by peaks in establishment, are indicative of large-scale disturbance events (e.g. logging, fire, and windthrow) that clear

previously forested areas and allow a new cohort of trees to establish (Lorimer, 1980; Oliver, 1981; Abrams et al., 1995). Early radial growth may be indicative of light availability at the time of establishment. Fast early growth among groups of trees reflect stand-clearing disturbance events that allow trees to ascend to canopy positions (Buttrick, 1917; Lorimer et al., 1988; Lorimer & Frelich, 1989; Rentch et al., 2003). Growth releases occur in understory trees when a gap is created by local disturbance or senescence of a canopy-dominant tree (Lorimer & Frelich, 1989; Rentch et al., 2003; Rubino & McCarthy, 2004) and indicate closed-canopy conditions. Therefore, trees initiating in open fields should have lower rates of disturbance (fewer growth releases) than old-growth forests where competition for light is intense (Lorimer et al., 1988; Lorimer & Frelich, 1989; Rentch et al., 2003).

Here, we compare recruitment, early radial growth, and growth releases in historic logs versus old-growth forests in the central Appalachian Mountains to test for extensive reforestation following depopulation and land abandonment. We include old-growth forests because many currently protected old-growth sites are unsuitable for human occupation and would likely not have experienced strong effects of abandonment on recruitment or growth. We hypothesize that compared to old-growth forests, historic logs will have evidence of land abandonment through 1) synchronous recruitment following depopulation, 2) rapid early growth, and 3) few growth releases.

STUDY AREA, MATERIALS, AND METHODS

CLIMATE AND VEGETATION

The study area is in the central Appalachian Mountains of eastern North America along the border of West Virginia and Virginia, USA. Sites are located in the Ridge and Valley and Appalachian Plateau physiographic provinces (Fig. 1), which are both generally characterized by deep valleys flanked by narrow, forested mountain ridges (Fralish, 2003). We selected this study area because it provides: 1) distinctly different topographic sites (upland valleys (historic buildings) vs. hillslopes (old-growth forests)), 2) numerous previously undated historic log buildings for sampling, and 3) a region not historically recognized as densely populated by Indigenous Peoples. Thus, if there is evidence of reforestation here, then it is also likely to be found in more densely populated regions.

The region is characterized by temperate climate, with average temperatures ranging from -6.6–4.4°C (January) to 15.6–26.7°C (July), and average precipitation ranging from 50.9–152.4 mm annually (NCEI, 2019). The region is part of the mesophytic Appalachian oak section of the eastern deciduous forest and is dominated by oaks (*Quercus* spp.), hickories (*Carya* spp.), tulip poplar (*Liriodendron tulipifera*), and pines (*Pinus* spp.) (Braun, 1950; Dyer, 2006). Gap-phase dynamics are common in mature stands (Runkle & Yetter, 1987; Rentch et al., 2003), while windthrow and (human-ignited) fire are historically common disturbance processes (Abrams, 1992; Delcourt & Delcourt, 1997; Hessl et al., 2011).

LAND-USE HISTORY

Though archaeological evidence of late prehistoric (1000–1700 CE) to historic (post-1700 CE) occupation of Indigenous Peoples in the study area is sparse (McMichael, 1968; Spencer, 2016), the general region (including West Virginia, Virginia, and Maryland) was inhabited by

Iroquoian, Algonquian, and Siouan speaking peoples (Kercheval, 1902; Swanton, 1943; McMichael, 1968; Potter, 1993; Wall & Lapham, 2003). Indigenous peoples of this region likely sought fertile river valleys for agriculture and villages, used girdling and fire to clear land, and used stone tools to fell smaller trees for housing, palisades, and fuel (Williams, 1989; Denevan, 1992; Potter, 1993; Springer et al., 2010; Munoz et al., 2014a). European immigrants began inhabiting the study area between the 1740s and 1760s (Kercheval, 1902; Brooks, 1911; Dayton, 1942), and their descriptions of the landscape vary. While many European accounts detail dense forests, some describe large clearings attributed to indigenous land use (see Denevan (1992) and Williams (1989) and references therein). In what is now West Virginia, one European traveler in 1752 noted “a great many cleared fields”, and another in 1769 noted “stands of trees uniform in growth”, and about 100 years old, “some of which were growing up through the cobblestone floors used by the Indians” (Maxwell, 1910; Williams, 1989). The depopulation of most Indigenous Peoples from the study area likely occurred in the 1600s (Jones, 2014); however, some Indigenous Peoples were still inhabiting the region alongside European immigrants into the 1770s (Kercheval, 1902).

TREE-RING DATING OF SITES

We collected samples from 18 historic log buildings (1700s–1800s CE) in upland valleys in West Virginia and Virginia (Figs. 1 & 2) based on the following criteria: 1) constructed with hand tools to ensure the trees were felled on site; 2) ≥ 10 logs available for sampling; and 3) buildings constructed with species with existing regional reference chronologies for crossdating. We selected eight old-growth sites for comparison based on the following criteria: 1) mean series length > 150 years; 2) the same species represented in historic logs; and 3) sites in proximity to historic log buildings (Fig. 1; see also Table S1.1, Appendix S1 in Supporting Information). The historic log buildings used in this study reflect European immigrants’ preference for home sites and therefore represent upland valleys suitable for human occupation. Likewise, the old-growth forests used here were collected from long-lived trees in remote locations. Additionally, we collected samples from ten white oak (*Quercus alba*) trees in a forested stand that established in an abandoned field (c. 1930s–1940s) adjacent to one of our historic sites to provide a reference for the early radial growth pattern of trees establishing in abandoned fields (hereafter: ‘reference site’) (Fig. S2.1, Appendix S2). We removed all duplicate cores (additional samples from the same tree/log) from each chronology to reduce the risk of representing a historic log, old-growth tree, or reference site tree more than once in our analyses. Whenever possible, we retained the core with the most rings for use in analyses.

To identify felling dates of historic log buildings, we collected 14 mm core samples from ≥ 2 logs per wall that displayed outer edge characteristics (e.g. bark, rounding). Cores were taken from the basal end of logs to obtain the maximum number of inner rings. Logs are often harvested ~30 cm above the tree base (Quigley, 1954), while cores are often collected from live trees at breast height (~140 cm) (Speer, 2010), producing some uncertainty in estimates of inner ring dates from both historic logs and live trees. All core samples were mounted and sanded using progressively finer sanding grits (100–800 ANSI-grit) to display cellular structure and ring boundaries. We measured ring widths to the nearest 0.001 mm using a Velmex sliding-stage micrometer and the program TELLERVO (Brewer et al., 2011). We statistically crossdated all tree-ring series using the program COFECHA (Holmes, 1983) and compared each series with regional tree-ring chronologies from the International Tree Ring Data Bank (ITRDB)

(<https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring>). All outer rings of historic log samples were inspected to determine terminal ring attributes and felling years (Bannister, 1962; Nash, 1999).

RECRUITMENT

We used the innermost rings of historic logs and old-growth trees to assess whether there was a recruitment pulse in historic logs following abandonment that was absent from old-growth forests. Inner ring dates are not germination dates but instead represent age at coring height (Villalba & Veblen, 1997) and are hereafter referred to as recruitment dates. We used pith indicators, concentric circles of varying sizes on transparency sheets, to estimate the number of missing rings (pith offset; PO) of historic log samples in which pith was not sampled. To estimate the PO of historic samples lacking curvature, we shifted inner ring dates by a fixed PO of 20 years (EPO). Actual inner ring (pith) dates are unknown for old-growth sites (these data were not reported by the original authors) so only innermost ring dates (no pith offset; NPO) were used in this case.

Trees may have been selected for construction based on similar log sizes, though this does not always constrain the ages of samples to one age group (Pederson, 2010; de Graauw, 2017). To assess if recruitment dates were a function of selection bias, we: 1) compared the series length (number of rings) of historic logs to diameter; 2) compared ages of trees with felling dates to assess whether samples were aging through time (i.e. trees felled for 1700's buildings would have fewer rings than trees felled for 1800's buildings) as logs were successively felled from forests following abandonment; and 3) compared felling dates and diameter of each log as an additional test of the age/size relationship.

EARLY GROWTH

We calculated early radial growth using standardized tree-ring series with no offset and two treatments to evaluate the effects of pith offset. First, we standardized the raw ring-width values in each sample, aligned all ring-width series by cambial age (ring number from pith) at the innermost ring (NPO), and created site means for historic sites, old-growth sites, and the reference site. We visually compared each of the NPO site means (historic and old-growth sites) with the reference site to assess whether early growth was consistent with fast-growing trees in open fields. We separated sites according to two early growth patterns (fast vs. slow growth) based on visual comparison (Table S2.1, Appendix S2). We then used 'kmeans' cluster analysis (stats v3.6.1) in base R (R Core Team, 2013) to quantitatively separate historic and old-growth sites into two groups based on early growth patterns (fast vs. slow growth). We then used those clusters to determine how many sites (historic and old-growth) had fast versus slow early growth in the first 100 years and to determine if trees in the fast-growing sites established earlier, during the period of depopulation, relative to slow-growing sites.

Next, we examined the effects of adjusting series according to PO. Cluster analysis requires values for every observation, therefore, we replaced the missing values created by PO with the mean of the first three (PO3) and first five (PO5) years of standardized mean ring widths. To objectively categorize sites as having either early fast or slow growth, we again used cluster analysis on growth during the first 100 years. We then compared cluster assignments of the three sets of site means (NPO, PO3, PO5).

DISTURBANCE RECONSTRUCTION

We used percent change in radial growth to identify and compare growth releases at historic and old-growth sites (Lorimer & Frelich, 1989). We evaluated multiple disturbance detection methods (Fig. S3.1, Appendix S3) using the R package ‘TRADER’ (v1.2-3) (R Core Team, 2013; Altman et al., 2014). Here, we used a hybrid approach (‘mid-canopy growth averaging’) because of its ability to capture events recorded by both canopy-dominant and understory trees. We evaluated growth changes within a window length of 25 years (12 years prior to and after current year) and growth release thresholds (moderate: 35% growth increase; major: 70% growth increase) from radial growth averaging (Lorimer & Frelich, 1989; Nowacki & Abrams, 1997) disturbance detection methods. We combined the outputs (moderate and major releases) to determine if a growth release occurred for each sample in a given year. Results based on other disturbance detection methods are available in Appendix S3 (Figs. S3.2–S3.27).

To account for unequal numbers of samples between sites and the increased rate of disturbance with sample size (Fig. S3.28, Appendix S3), we used the bootstrap method to resample the disturbance histories of 10 trees 1000 times at each site, estimate the percentage of trees recording release events in each year, and estimate the 95% CLs around those estimates. Using these estimates we compared the disturbance rate (release events per 100 years) of site types (historic vs. old-growth) and cluster types (fast vs. slow) using the ‘ANOVA’ function (car v3.0-3) in base R (R Core Team, 2013).

RESULTS

TREE-RING DATING OF SITES

We identified the felling dates (1784–1874 CE) of 18 historic log buildings (Table 1) located in upland valley settings. 16 buildings were constructed from white oak and two were constructed from tulip poplar (Table 1). Of the eight old-growth sites, six were white oak and two were tulip poplar (Table 2). Series intercorrelations for old-growth sites (*mean* = 0.579, *range* = 0.504–0.680) are equivalent to those of historic buildings (*mean* = 0.592, *range* = 0.507–0.695) ($t_{14} = 0.539$, $p > 0.001$). Comparisons of detrended mean ring-width chronologies for old-growth and historic sites are reported in Appendix S1 (Figs. S1.1–S1.3 & S1.4–S1.19, respectively).

RECRUITMENT

We estimated PO for 270 (75%) of 361 historic logs. Of those, 1% contained pith, 6% had a PO of <5 rings, and 93% had a PO of ~5–15 rings (Table S1.2, Appendix S1). For the remaining 25% of samples, we added a fixed pith offset of 20 years (EPO). Using inner ring dates with no offset (NPO), we observed a period of elevated recruitment across historic sites ($\geq 10\%$ of trees/decade) between 1690 and 1730, with the highest period of recruitment occurring in the 1710s and 1720s (each ~13% of total recruitment) (Fig. 3a). Using PO and EPO dates, we observed elevated recruitment between 1680 and 1710, with the period of highest recruitment occurring in the 1690s (~15% of total recruitment) (Fig. 3b). At old-growth sites, using only inner ring dates, there was a similar recruitment event between 1670 and 1740, though a lower percentage of trees recruited in those decades ($\geq 5\%$ of trees/decade) (Fig. 3c). Prior to the 1670s, there is comparatively little evidence of recruitment at either historic or old-growth sites.

Analyses of the relationship between series length and tree diameter suggest there is a weak but positive correlation for historic logs ($R^2 = 0.071$, $p \leq 0.001$) reflecting a weak selection bias in tree age, given the range of log diameters in the sample (range = 18.5–40.2 cm). Historic oak series increase in length (age over time) ($R^2 = 0.172$, $p \leq 0.001$), consistent with an aging forest (Fig. 3d). Two early sites (MC and SCQ), where trees were among the oldest at the time of felling, are outliers in this overall trend (Fig. 3d). There is a similar weak but positive relationship between felling date and log size ($R^2 = 0.071$, $p \leq 0.001$) that could partially explain increasing series length with time.

EARLY GROWTH

Early radial growth at the reference site (Table 1) was characterized by 45 years of fast initial growth (y-intercept = ~ 2.0 , growth declining exponentially) (Fig. 4a). Using the NPO dataset, cluster analysis independently separated historic and old-growth sites into either: 1) rapid early growth (y-intercept = ~ 2.0 , growth declining exponentially for ~ 80 years) (Fig. S2.27, Appendix S2, Fig. 4b) associated with high-light conditions in second-growth forests or 2) slow early growth (y-intercept = ~ 1.5 , growth declining exponentially for ~ 20 years) (Fig. 4c) typical of understory trees in low-light conditions under the closed canopy of a mature forest. The mean recruitment date of all series from sites in the fast-growth cluster (1719 CE, 95% CI [1713, 1725]) was older than the mean recruitment date of all series from sites in the slow-growth cluster (1748 CE, 95% CI [1740, 1756]) ($t_{553} = 5.9$, $p \leq 0.001$) (Fig. 4d), indicating that trees that recruited earlier were more likely to have fast early growth.

Cluster analysis of the NPO data assigned most historic sites (61%) to the fast-growth cluster (Fig. 4e) and all old-growth sites (100%) to the slow-growth cluster (Fig. 4f). Using the PO3 and PO5 treatments, most historic sites were assigned to the fast-growth cluster (67%–83%) and most old-growth sites were assigned to the slow-growth cluster (87.5%–100%) (Tables S2.1 & S2.2, Figs. S2.28–S2.29, Appendix S2). In subsequent analyses, we use cluster assignments for NPO because it provides equivalent treatment of data from historic sites with those of old-growth sites, for which we were unable to estimate PO.

DISTURBANCE RATE

To determine if there were differences in disturbance rate (bootstrapped release events per 100 years), we used one-way ANOVA and Tukey HSD on cluster (fast and slow) and site type (historic and old growth). Because no old-growth sites were assigned to the fast-growth cluster, there was no ‘fast old-growth’ group. There was a significant difference in mean disturbance rate between combined cluster and site type groups ($F_{2,23} = 15.49$, $p \leq 0.001$). Levene’s test indicated equal variances ($F_{2,23} = 3.23$, $p = 0.058$). There was no difference in mean disturbance rate between the ‘slow old-growth’ group and the ‘slow historic’ group ($p > 0.001$), nor was there a difference in mean disturbance rate between the ‘slow historic’ group and the ‘fast historic’ group ($p > 0.001$). However, the mean disturbance rate was lower in the ‘fast historic’ group (5.3 events/century, 95% CI [3.6, 7.0]) than in the ‘slow old-growth’ group (23.5 events/century, 95% CI [17.5, 29.5]) ($p \leq 0.001$) (Fig. 5). See Appendix S3 for actual and bootstrapped release events with 95% confidence limits for all sites (Figs. S3.29–S3.54), combined bootstrapped releases by site type (Figs. S3.55–S3.56), and a comparison of bootstrapped release events by site type over the common period (Fig. S3.57).

DISCUSSION

It has been proposed that widespread depopulation of Indigenous Peoples in the Americas beginning in 1492 might have led to extensive reforestation in subsequent decades (Dull et al., 2010; Nevle et al., 2011; Lewis & Maslin, 2015; Koch et al., 2019). We expected that if forests experienced widespread changes in recruitment and density due to land abandonment, logs sampled from historic buildings located in upland sites would be most likely to capture those changes through a pulse in recruitment, fast early growth, and low rates of disturbance in second-growth stands. Indeed, our data, though limited in geographic scope, largely support the idea of reforestation following the depopulation of Indigenous Peoples in our study region, though the exact land use changes driving forest regrowth remain uncertain.

RECRUITMENT IN HISTORIC LOG RECORD

We identified a recruitment pulse at historic log sites that is independent of building age. Few trees recruited at historic log sites until the 1670s and there was a period of elevated recruitment from the 1690s to the 1730s (Fig. 3a). One of the highest periods of recruitment, during the 1710s, included the greatest number of logs for which we were unable to estimate PO (i.e. samples with no curvature). This suggests their actual pith dates were at least two decades prior to the inner ring dates in the 1710s, likely recruiting in the 1690s or earlier (Fig. 3b). The period of heightened recruitment at historic sites is independent of maximum log ages (150-year-old individuals), as buildings with trees felled in both the 1780s and 1880s recruited in the 1690s–1710s. While most historic oak series increased in length (aged over time), consistent with an aging forest, SCQ and MC were among the oldest sites (felling dates of 1784 and 1794, respectively) and the oldest trees (max series length of 168 and 209 years, respectively) (Fig. 3d). These sites might reflect extant forested areas from the time of indigenous occupation.

Though we collected samples at the basal end of logs whenever possible, we cannot account for the height at which logs were felled. Yet, the pattern of recruitment that we observe is consistent with the timing of depopulation in the region (c. 1600s) (Wall & Lapham, 2003; Jones, 2014), especially given the time required for forest establishment following land abandonment, estimated at ~15–20 years in eastern North America (Oliver, 1981; Harrison & Werner, 1984; Myster, 1993).

While the timing of recruitment is consistent with abandonment, the pattern of recruitment at old-growth sites is similar to that of historic logs, suggesting that recruitment may not have been driven exclusively by land abandonment. At old-growth sites, we observed an absence of recruitment until the 1670s followed by elevated recruitment until the 1740s (Fig. 3c). These dates are likely biased towards more recent decades since we were not able to estimate how close samples were to the pith or the height at which samples were taken (Villalba & Veblen, 1997). Recognizing that old-growth sites were predominantly located on low-productivity sites that were less suitable for agriculture (Table 2), this synchronous event at both site types (historic and old growth) is not consistent with agricultural clearing. It is, however, consistent with a recruitment event previously documented throughout eastern North America in live trees, historic logs, and archaeological samples (Pederson et al., 2014 and references therein; Trouet et al., 2018). Evidence of this recruitment pulse across both site types suggests that recruitment may have been associated with regional climate variability rather than, or in addition to, land

abandonment. Pederson et al. (2014) suggest that mortality, following a sub-continental drought allowed for elevated recruitment during a subsequent pluvial period.

Another possible explanation for the period of recruitment observed in both historic buildings and old growth sites is the cessation of both high-intensity (agriculture) and low-intensity land use by Indigenous Peoples. There is ample evidence of fire activity in eastern North America prior to European immigration that may reflect indigenous land management practices (e.g. Delcourt & Delcourt, 1997; Guyette et al., 2002; Black et al., 2006; Springer et al., 2010). The absence of fire following depopulation might have led to increases in forest recruitment across site types; however, studies of modern fire cessation have shown mesic species tend to recruit under these conditions, not fire-adapted species such as oaks (Nowacki & Abrams, 2008; Flatley et al., 2015). A high-resolution sediment charcoal record from a montane lake near our study area (Trout Pond; Fig. 1) indicates fire occurred regularly over the last 1000 years (Lynch and Clark (2002) as cited in Lafon et al., 2017). Notably, there is a 2- to 3-decade long period beginning in ~1650 CE in which no charcoal accumulation occurs, and it is the longest charcoal-free span in the 1000-year record. This anomaly in the otherwise charcoal-rich record from Trout Pond coincides with the period of recruitment we see in historic and old-growth trees and with the proposed period of depopulation in this region, suggesting a variety of indigenous land management techniques, including fire in the old-growth sites, could have been employed and then abandoned ~1650 CE. A similar fire-free period was documented in ~1675 CE in Indiana and was attributed to the depopulation of Indigenous Peoples from that area (Guyette et al., 2003), though tree recruitment and growth were not evaluated.

EARLY GROWTH IN HISTORIC LOG RECORD

Our analysis of early radial growth trends supports the hypothesis that most, though not all, historic trees were felled from rapidly growing (second-growth) forests. Most historic sites (between 11–15 of 18) fell within the fast-growth cluster (Fig. 4e; Table S2.2, Appendix S2), typical of trees growing in high-light conditions. All eight old-growth sites, and seven historic sites, were slow-growing (Fig. 4f). Further, the series in the fast-growth cluster had earlier recruitment dates than those in the slow-growth cluster (Fig. 4d), suggesting that the trees that recruited after depopulation were faster-growing than trees that recruited later when light availability may have attenuated. If there was a period of rapid initial growth in old-growth sites, it is likely that we did not capture it, since there was no evidence that samples were close to, or included, pith. Similarly, initial growth at historic sites may have been more rapid than our results indicate since we cannot account for the height at which logs were felled. Nevertheless, our results suggest most, though not all, historic sites were composed of trees that established in high-light conditions, consistent with the pattern of growth we observed in our reference site. In contrast, all old-growth sites were composed of trees that established in low-light conditions, consistent with mature forests. Despite synchronous recruitment across historic and old-growth sites, these patterns of early radial growth suggest that historic trees initiated under higher levels of light-availability than old-growth trees during the same period.

GROWTH RELEASES IN HISTORIC LOG RECORD

Our results support the hypothesis that historic sites with fast early growth had fewer growth releases than old-growth sites, a pattern consistent with the expectation that fast-growing trees in high light conditions would have fewer growth releases than slow-growing trees in closed-

canopy forests (Buttrick, 1917; Lorimer et al., 1988; Lorimer & Frelich, 1989; Rentch et al., 2003). However, among the historic sites, there was no significant difference in fast-growth versus slow-growth sites. These results suggest that the sites themselves, located in upland areas, may have experienced less disturbance than other locations, such as hillslopes, regardless of previous land management. For example, Foster (1988) observed that the rate of disturbance increased with increasing topographic position and exposure to wind. Additional work on disturbance rates and their relationship to successional stage and topographic position (upland valleys vs. hillslopes) is required to assess the utility of this measure in evaluating past land use.

EVALUATING THE EXTENSIVE FOREST REGROWTH MODEL

The idea that the depopulation of Indigenous Peoples in the Americas beginning in 1492 led to widespread reforestation, carbon drawdown, and global-scale cooling (Dull et al., 2010; Koch et al., 2019) hinges on three assumptions: 1) the timing of depopulation in the 1500s was coincident with CO₂ drawdown, 2) Indigenous Peoples' land use was intensive enough to result in cleared (or thinned) and subsequently reforested areas, and 3) the spatial extent of their impact was sufficient to affect global CO₂ levels. While European diseases undoubtedly affected Indigenous Peoples, there is spatiotemporal complexity in the spread of disease, dictated by population sizes, interactions, and physical geography (Ramenofsky et al., 2003; Jones, 2014), which suggests depopulation of Indigenous Peoples in North America following European contact likely occurred between 1518 and 1789 CE (Jones, 2014). Estimates of the timing of depopulation within our study area range from 1600 to 1677 CE (Jones, 2014), overlapping with the timing of modeled depopulation, reforestation, and carbon drawdown (~1570–1650 CE).

Our analysis of recruitment, early growth, and growth releases suggests that 1) a major recruitment event coincided with the estimated timing of depopulation in this region, and 2) trees in most, but not all, historic log buildings were felled from second-growth forests while trees in all old-growth sites had early growth and growth releases consistent with that of mature, closed canopy forests. While the timing of depopulation and reforestation in this region is not contemporaneous with the nadir of carbon drawdown in the extensive forest regrowth model (~1610 CE), it is consistent with the subsequent period of low atmospheric CO₂ (~1650–1750 CE). Our study region is small, however, and is not an area recognized for dense indigenous populations. Depopulation and reforestation in other locations, particularly the neo-tropics, would have had a much larger effect on atmospheric CO₂ and would have occurred earlier, coincident with the CO₂ minimum ~1610 CE (Dull et al., 2010). Further, our study of reforestation is limited to upland valleys and does not reflect the forested landscape as a whole. Other regions in eastern North America, with known histories of high-intensity land use, such as floodplains, which some indigenous cultures may have preferred as agricultural sites, may reveal stronger signals of clearing and regrowth (Munoz et al., 2014b; Stinchcomb et al., 2011; Bird et al., 2017). Similar studies conducted in areas such as the Mississippi River Valley, where human populations were higher (e.g. Munoz et al., 2014b) would improve our understanding of the timing of depopulation, reforestation, and carbon drawdown.

Finally, it is likely that indigenous land management was diverse and included high- and low-intensity techniques (Doolittle, 1992; Black et al., 2006; Gremillion, 2015) reflective of the diversity of cultures and peoples present at the time of contact. As a result, depopulation may

have led to a variety of ecological responses, even in similar locations (e.g. McEwan & McCarthy, 2008). Many of these land management techniques may be difficult to detect in the rings of historic logs alone but may be uncovered through exploration of multiple data sources such as high-resolution charcoal, archaeological records, and ethnographic materials.

CONCLUSIONS

Our study contributes empirical evidence from eastern North America to assess whether depopulation of Indigenous Peoples resulted in reforestation of abandoned land. While our results of forest recruitment, early radial growth patterns, and growth releases generally support the idea of reforestation following depopulation, the timing of these events in our study area is later than the nadir of reforestation and carbon drawdown in the extensive forest regrowth model (~1610 CE). However, our evidence of reforestation (c. 1670s) in an area not recognized for dense indigenous populations, suggests that earlier reforestation following depopulation may have occurred in more densely populated regions.

Additionally, the forest recruitment event that we observed across historic and old-growth sites has been documented elsewhere in eastern North America. It is possible that a previously recognized sub-continental drought and subsequent pluvial (Pederson et al., 2014) contributed to the recruitment event observed in this region, however, early radial growth and growth releases were different among most historic sites and all old-growth sites, suggesting that the drought/pluvial event alone may not account for the open-growth conditions at historic sites. Comparisons of recruitment and growth in areas where the regional drought event and depopulation were not contemporaneous may help to disentangle these events.

Finally, the novel data and techniques employed here yielded new insights about Indigenous Peoples' impacts on forests in a place where archaeological and ethnographic data were limited. If these results are replicated in a broader region, it would suggest that upland forests at the time of European immigration may have been a legacy of indigenous land-use practices, an inference that substantially alters our understanding of eastern deciduous forest dynamics. We suggest future research focus on: 1) targeting older log buildings (constructed c. 1600s–1700s CE) that would fully cover the period of depopulation; 2) selecting areas for which archaeological records of Indigenous Peoples, their land-use strategies, and the timing of depopulation are better documented (e.g. Liebmann et al., 2016); and 3) combining paleoecological data sources with historical, ethnographic, and archaeological approaches to better define the nature of indigenous land-use practices prior to contact. The timing of a regional drought event, depopulation, and subsequent mass recruitment of trees, all within the period of ~1650–1690 CE, is compelling and warrants further research into interactions between indigenous land use and climatic events during a pivotal period in North American history.

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Table 1. Summary of dendroarchaeological dating results (Series IC: series intercorrelations), locations, and general landscape type for each historic log building. QUAL: white oak (*Quercus alba*), LITU: tulip poplar (*Liriodendron tulipifera*). Sites BAR1 and BAR2 are located on the same site, as are sites CB and CY. Site RC is adjacent to the early growth reference site.

ID	Building Name	Species	Trees	Span	Series IC	Felling Date	Coordinates	Landscape
BAR1	Barracks	QUAL	24	1683-1799	0.689	1799	37.80, -80.44	upland valley
BAR2	Barracks Addition	QUAL	13	1698-1877	0.590	1877	---	---
CB	Caraway Barn	QUAL	17	1682-1824	0.566	1824	38.04, -80.30	upland valley
CY	Caraway House	QUAL	22	1680-1804	0.577	1804	---	---
DB	Diamond Barn	QUAL	23	1684-1786	0.668	1786	38.15, -80.20	upland valley
JJJ	James Jarrett House	QUAL	15	1674-1792	0.621	1792	37.77, -80.63	upland valley
KML	Kee Cabin	LITU	17	1777-1865	0.578	1865	38.20, -80.11	upland valley
KQ	Kile Homestead	QUAL	16	1691-1833	0.522	1833	38.77, -79.28	upland valley
MC	Mallow Church	QUAL	16	1586-1794	0.536	1794	38.77, -79.26	hill
MCF	McCoy Fort	QUAL	17	1684-1871	0.659	1799	37.99, -80.48	upland valley
MP	Mill Point Barn	QUAL	44	1688-1851	0.625	1851	38.16, -80.18	hill
PB	Pitsenbarger Barn	QUAL	18	1714-1840	0.514	1840	38.58, -79.30	hill
RC	Rimer Cabin	QUAL	16	1675-1840	0.507	1840	38.45, -79.53	upland valley
SC	Sisler Cabin	LITU	17	1719-1869	0.530	1869	38.07, -80.29	upland valley
SCQ	Stump Cabin	QUAL	27	1645-1784	0.567	1784	38.91, -79.02	upland valley
SH	Sydenstricker House	QUAL	28	1690-1831	0.695	1831	37.74, -80.54	upland valley
WBQ	Whiskey Barn	QUAL	12	1725-1844	0.555	1844	38.71, -79.31	upland valley
ZH	Zigafuss House	QUAL	19	1675-1874	0.662	1874	37.91, -80.62	upland valley

Table 2. Summary of old-growth site characteristics used in this study. Series IC: Series Intercorrelations, QUAL: white oak (*Quercus alba*), LITU: tulip poplar (*Liriodendron tulipifera*). See Table S1.1, Appendix S1 in Supporting Information for data sources.

ID	Site Name	Species	Trees	Span	Series IC	Coordinates	General Landscape
CFQ	Carnifex Ferry	QUAL	20	1670-2013	0.544	38.21, -80.94	mountain slope
FGT	Fiddler's Green	LITU	22	1677-2002	0.680	37.89, -85.93	mountain slope
KY003	Lilly Cornett Tract	QUAL	40	1660-1982	0.625	37.10, -84.20	mountain slope
KYLD	KY London District	LITU	13	1649-2007	0.504	37.08, -83.00	mountain slope
VA011	Mountain Lake	QUAL	26	1552-1983	0.602	37.38, -80.50	mountain slope
VA017	Patty's Oaks	QUAL	23	1569-1982	0.517	37.92, -79.80	mountain slope
VA029	Craig Creek	QUAL	20	1722-2001	0.592	37.35, -80.37	mountain slope
VA037	Stadium Woods	QUAL	33	1697-2011	0.565	37.22, -80.42	upland valley

Figure 1. Locations of 18 historic log buildings (circles) and 8 old-growth sites (triangles) within the central Appalachian region, USA. Black symbols represent white oak (*Quercus alba*) sites and white symbols represent tulip poplar (*Liriodendron tulipifera*) sites. The sediment charcoal site (Lynch and Clark (2002) as cited in Lafon et al., 2017) is represented by a black cross.

Figure 2. Examples of historic log buildings used in this study: (a) Whiskey Barn (WBQ), white oak (*Quercus alba*), inferred construction in 1844; (b) Carraway House (CY), white oak, inferred construction in 1804; (c) Sisler Cabin (SC), tulip poplar (*Liriodendron tulipifera*), inferred construction in 1869; (d) Stump Cabin (SCQ), white oak, inferred construction in 1784. Photos: K. de Graauw.

Figure 3. Percent of historic logs (a) and old-growth trees (c) recruiting in each decade (1550–1940) using unadjusted innermost ring dates. Percent of historic logs recruiting (b) in each decade (1550–1810) using estimated number of rings to pith (pith offset (PO)) and estimated pith offset (EPO), a 20-year shift of inner rings in samples lacking curvature. The curvilinear relationship between ages of individual logs from all historic white oak (*Quercus alba*) sites and felling dates ($R^2 = 0.172$, $p \leq 0.001$) (d).

Figure 4. Mean early growth (standardized mean ring widths with 95% confidence limits, aligned by cambial age at innermost ring with no pith offset (NPO)) at the modern reference site (a) over the first 55 years, and of all sites assigned to fast (b) and slow (c) growth clusters using cluster analysis over the first 100 years of growth. Inner ring dates (NPO) (d) of series from sites assigned to the two early growth clusters (fast vs. slow). Mean (red diamonds) and median (black lines) disturbance rates are shown, and boxes indicate the 25th and 75th percentiles. Percent and number of historic and old-growth sites assigned to the fast growth cluster (e) and slow growth cluster (f).

Figure 5. Comparison of mean disturbance rate (bootstrapped release events per 100 years with 95% confidence limits) of combined cluster (fast and slow) and site (historic and old growth) groups. There was no ‘fast old-growth’ group identified in cluster analysis. Red diamonds indicate the mean disturbance rate, black lines indicate the median disturbance rate, and boxes indicate the 25th and 75th percentiles.

SUPPORTING INFORMATION

Do historic log buildings provide evidence of reforestation following depopulation of Indigenous Peoples?

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Appendix S1 – Tree-Ring Dating and Pith Offset

Old-growth Data Sources

Table S1.1. Data sources for old-growth sites. Sites collected from the International Tree Ring Data Bank (ITRDB) are available online at National Oceanic and Atmospheric Administration (NOAA) Paleoclimatology Program and World Data Center for Paleoclimatology (<http://www.ncdc.noaa.gov/paleo/>). Sites indicated as published are from collections not on the ITRDB, but which were previously published in scientific journals (references in Appendix S1).

ID	Site Name	Collection	Citation
CFQ	Carnifex Ferry	ITRDB	Cockrell et al., 2017
FGT	Fiddler's Green	published	Maxwell et al., 2011
KY003	Lilly Cornett Tract	ITRDB	Cook, 1982b
KYLD	KY London District	published	Pederson et al., 2012
VA011	Mountain Lake	ITRDB	Cook, 1983
VA017	Patty's Oaks	ITRDB	Cook, 1982a
VA029	Craig Creek	ITRDB	Copenheaver, 2001
VA037	Stadium Woods	ITRDB	Copenheaver et al., 2014

Old-Growth Chronologies

Crossdating of old-growth chronologies, sorted by species (white oak (*Quercus alba*) and tulip poplar (*Liriodendron tulipifera*)) and by proximity to one another. Series are detrended using the “Modified Negative Exponential” detrending option in dplR (Bunn et al., 2018). Vertical red lines are to illustrate low growth years in common across chronologies.

Figure S1.1. Crossdating of old-growth *Quercus alba* sites, KY003 (Kentucky) and CFQ (West Virginia). Red lines indicate examples of common marker years.

Figure S1.2. Crossdating of old-growth *Quercus alba* sites VA011, VA017, VA029, VA037 (all in Virginia). Red lines indicate examples of common marker years.

Figure S1.3. Crossdating of old-growth *Liriodendron tulipifera* sites, KYLD and FGT. Red lines indicate examples of common marker years.

Crossdating of Historic Sites

Crossdating of historic sites against old-growth reference chronologies. Series are detrended using the “Modified Negative Exponential” detrending option in dplR (Bunn et al., 2018). Vertical red lines are to illustrate certain low growth years in common across chronologies.

Figure S1.4. Sites BAR1 and BAR2 (same location) compared with old-growth reference site CFQ. All *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.5. Sites CY and CB (same location) compared with old-growth reference site CFQ. All *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.6. Site DB compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.7. Site JJJ compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.8. Site KML (*Liriodendron tulipifera*) compared with old-growth reference site FGT (*Liriodendron tulipifera*). Red lines indicate examples of common marker years.

Figure S1.9. Site KQ compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.10. Site MC compared with old-growth reference sites CFQ (West Virginia) and VA011 (Virginia). All *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.11. Site MCF compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.12. Site MP compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.13. Site PB compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.14. Site RC compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.15. Site SC (*Liriodendron tulipifera*) compared with old-growth reference site FGT (*Liriodendron tulipifera*). Red lines indicate examples of common marker years.

Figure S1.16. Site SCQ compared with old-growth reference sites CFQ (West Virginia) and VA011 (Virginia). All *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.17. Site SH compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.18. Site WBQ compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Figure S1.19. Site ZH compared with old-growth reference site CFQ. Both *Quercus alba*. Red lines indicate examples of common marker years.

Pith Offset

Table S1.2. Number of historic log samples with pith and pith offset (PO), estimated using pith indicators. Samples with < 5 rings were very near pith while samples > 15 rings showed no signs of curvature, so we applied a 20-year pith offset (EPO).

Site ID	Pith	PO (< 5 rings)	PO (5 – 15 rings)	EPO (>15 rings)
<i>BARI</i>	1	2	16	5
<i>BAR2</i>	0	0	8	5
<i>CB</i>	0	1	15	1
<i>CY</i>	0	1	20	1
<i>DB</i>	0	1	19	3
<i>JJJ</i>	1	0	13	1
<i>KML</i>	0	0	15	2
<i>KQ</i>	0	0	11	5
<i>MC</i>	0	0	13	3
<i>MCF</i>	0	0	9	8
<i>MP</i>	0	1	27	16
<i>PB</i>	0	3	6	9
<i>RC</i>	0	0	11	5
<i>SC</i>	0	2	14	1
<i>SCQ</i>	1	0	18	8
<i>SH</i>	0	1	15	12
<i>WBQ</i>	0	1	8	3
<i>ZH</i>	0	2	14	3
<i>Total</i>	3	15	252	91

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SUPPORTING INFORMATION

Do historic log buildings provide evidence of reforestation following depopulation of Indigenous Peoples?

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Appendix S2 – Early Radial Growth

Table S2.1. Comparison of visual estimation with cluster assignments. Pith Offset: number of early growth years in which the mean site chronology had no values after aligning by pith offset (values = 0, at least one series had pith). Visual assessments were made using NPO data (no pith offset). Historic sites were analyzed using three treatments, NPO, PO3 (pith offset with 3-year mean), and PO5 (pith offset with 5-year mean). Because missing values are unknown for old-growth sites (*), all old-growth analyses include only NPO data. Highlighted cells: consistent cluster assignments across treatments.

Site	Pith Offset	Visual	NPO	PO3	PO5
BAR1	0	Fast	Fast	Fast	Fast
BAR2	5	Fast	Fast	Fast	Slow
CB	4	Slow	Slow	Fast	Slow
CY	4	Fast	Fast	Fast	Fast
DB	4	Slow	Slow	Fast	Slow
JJJ	0	Fast?	Fast	Fast	Fast
KML	7	Fast	Slow	Fast	Fast
KQ	8	Slow	Slow	Slow	Slow
MC	7	Fast	Fast	Slow	Slow
MCF	11	Fast	Fast	Fast	Fast
MP	4	Fast	Slow	Fast	Fast
PB	3	Fast	Slow	Fast	Fast
RC	5	Fast	Fast	Fast	Fast
SC	1	Fast	Fast	Fast	Fast
SCQ	0	Slow	Slow	Slow	Slow
SH	1	Slow?	Fast	Fast	Fast
WBQ	4	Fast	Fast	Fast	Fast
ZH	1	Fast	Fast	Fast	Fast
CFQ*	---	Fast	Slow	Slow	Slow
FGT*	---	Slow	Slow	Slow	Slow
KY003*	---	Slow	Slow	Slow	Slow
KYLD*	---	Fast	Slow	Fast	Slow
VA011*	---	Slow	Slow	Slow	Slow
VA017*	---	Slow	Slow	Slow	Slow
VA029*	---	Slow?	Slow	Slow	Slow
VA037*	---	Slow	Slow	Slow	Slow

Table S2.2. Overall results from cluster analysis by treatment.

	Fast		Slow	
<i>Treatment</i>	Historic	Old-Growth	Historic	Old-Growth
NPO	11 (61%)	0 (0%)	7 (39%)	8 (100%)
PO3	15 (83%)	1 (12.5%)	3 (17%)	7 (87.5%)
PO5	12 (67%)	0 (0%)	6 (33%)	8 (100%)

Figure S2.1. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site BAR1.

Figure S2.2. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site BAR2.

Figure S2.3. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site CB.

Figure S2.4. Standardized mean ring width in first 100 years for old-growth site CFQ.

Figure S2.5. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site CY.

Figure S2.6. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site DB.

Figure S2.7. Standardized mean ring width in first 100 years for old-growth site FGT.

Figure S2.8. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site JJJ.

Figure S2.9. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site KML.

Figure S2.10. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site KQ.

Figure S2.11. Standardized mean ring width in first 100 years for old-growth site KY003.

Figure S2.12. Standardized mean ring width in first 100 years for old-growth site KYLD.

Figure S2.13. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site MC.

Figure S2.14. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site MCF.

Figure S2.15. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site MP.

Figure S2.16. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site PB.

Figure S2.17. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site RC.

Figure S2.18. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site SC.

Figure S2.19. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site SCQ.

Figure S2.20. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site SH.

Figure S2.21. Standardized mean ring width in first 100 years for old-growth site VA011.

Figure S2.22. Standardized mean ring width in first 100 years for old-growth site VA017.

Figure S2.23. Standardized mean ring width in first 100 years for old-growth site VA029.

Figure S2.24. Standardized mean ring width in first 100 years for old-growth site VA037.

Figure S2.25. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site WBQ.

Figure S2.26. Standardized mean ring width in first 100 years: aligned by cambial age based on inner ring date (left) and aligned by cambial age after including pith offset (right) for historic site ZH.

Figure S2.27. Mean early growth (first 100 years) of sites, aligned by cambial age, no pith offset (NPO), and group by cluster assignments. Mean early growth of the cluster (all sites within each cluster) is indicated by a black line.

Figure S2.28. PO3: early growth patterns of standardized mean ring widths (with 95% confidence limits) aligned by cambial age with pith offset (3-yr mean).

Figure S2.29. PO5: early growth patterns of standardized mean ring widths (with 95% confidence limits) aligned by cambial age with pith offset (5-yr mean).

SUPPORTING INFORMATION

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Appendix S3 – Growth Releases

Disturbance Reconstruction

Growth releases in ring widths of trees or logs can be identified using several disturbance detection methods that have been developed to reconstruct non-stand-clearing disturbances (Lorimer & Frelich, 1989; Nowacki & Abrams, 1997; Black & Abrams, 2003; and others in Rubino & McCarthy, 2004). Growth averaging (Lorimer & Frelich, 1989), was developed to detect growth releases in shade-tolerant trees in closed canopy forests and compares mean growth 15 years prior to and after a given year (31-year window) to determine if an increase in growth has occurred at either the 50% or 100% level above previous growth, indicating moderate or major release events, respectively. Radial growth averaging, modified from the Lorimer & Frelich (1989) method specifically for canopy dominant, old-growth oaks in studies of pre-European settlement forest disturbance (Nowacki & Abrams, 1997), compares mean growth 10 years prior to and 10 years after a given year (21-year window) to determine if an increase in growth has occurred at either the 25% or 50% level above previous growth, indicating moderate or major release events respectively. However, it can both over-and-under-estimate release events if tree ages are not normally distributed (Rubino & McCarthy, 2004; Altman et al., 2014). The boundary line method was created to allow for analysis of uneven aged stands and growth changes for both canopy and understory trees (Black & Abrams, 2003; Black et al., 2009), and uses unique boundary line equations for common species, determined from radial growth rates prior to disturbance events (Altman et al., 2014). Boundary line parameters are calculated from modern trees and may be inappropriate for investigating trees that grew under different climatic scenarios (pre-and-post industrialization) and may not be useful in reconstructing disturbance events with annual resolution because of potential lag effects (Trotsiuk et al., 2018).

Mid-canopy Growth Averaging

For mid-canopy growth averaging, we split the difference between radial growth averaging and original growth averaging for window length and severity; calculated as a 25-year window length (12 years before and after the central year) and 35 and 70 percent severity for moderate and major releases, respectively.

Comparison of Disturbance Detection Methods

To evaluate the most appropriate detection method for historic logs we compared growth averaging (Lorimer & Frelich, 1989), radial growth averaging (Nowacki & Abrams, 1997), boundary line (Black & Abrams, 2003), and a fourth detection method, which we refer to as mid-canopy growth averaging. We used the R package TRADER (Altman et al., 2014) to apply these disturbance detection methods to our tree-ring series and compared the releases from all methods to aid in our

selection of the disturbance detection method that both captured important release events and eliminated noise. At historic sites the boundary line method recorded the most events (41%), followed by radial growth averaging (32%), mid-canopy growth averaging (18%), and original growth averaging (9%), while at old-growth sites radial growth averaging recorded the most events (38%), followed by the boundary line method (27%), mid-canopy growth averaging (24%), and original growth averaging (12%).

Historic and old-growth sites responded similarly to the four disturbance detection methods, excluding boundary line (BL), with historic sites recording the most events with the boundary line method and old-growth sites recording the most events with radial growth averaging (Fig. S3.1). In theory, both boundary line and mid-canopy growth averaging should capture releases in canopy-dominant and sub-canopy trees. We see similar records of release in the old-growth sites, with a 3% difference in recorded releases, but at historic sites there is a 23% difference in recorded releases.

Figure S3.1. Mean percent of release events by disturbance detection method (radial growth averaging (RGA), boundary line (BL), mid-canopy growth averaging (MGA), and original growth averaging (OGA)) for both site types, historic and old-growth. Error bars indicate standard deviation from the mean.

By-Site Disturbance Detection Comparisons

The following figures S3.2-S3.27 show by site comparisons of the number of trees recording a release event each year using four disturbance detection methods: boundary line method (BL; Black & Abrams, 2003), radial growth averaging (RGA; Nowacki & Abrams, 1997), mid-canopy growth averaging (MGA), and original growth averaging (OGA; Lorimer & Frelich, 1989). The total number of release events by method are indicated in parentheses by the detection method abbreviation.

Figure S3.2. Disturbance detection method comparison for historic site BAR1.

Figure S3.3. Disturbance detection method comparison for historic site BAR2.

Figure S3.4. Disturbance detection method comparison for historic site CB.

Figure S3.5. Disturbance detection method comparison for old-growth site CFQ.

Figure S3.6. Disturbance detection method comparison for historic site CY.

Figure S3.7. Disturbance detection method comparison for historic site DB.

Figure S3.8. Disturbance detection method comparison for old-growth site FGT.

Figure S3.9. Disturbance detection method comparison for historic site JJJ.

Figure S3.10. Disturbance detection method comparison for historic site KML.

Figure S3.11. Disturbance detection method comparison for historic site KQ.

Figure S3.12. Disturbance detection method comparison for old-growth site KY003.

Figure S3.13. Disturbance detection method comparison for old-growth site KYLD.

Figure S3.14. Disturbance detection method comparison for historic site MC.

Figure S3.15. Disturbance detection method comparison for historic site MCF.

Figure S3.16. Disturbance detection method comparison for historic site MP.

Figure S3.17. Disturbance detection method comparison for historic site PB.

Figure S3.18. Disturbance detection method comparison for historic site RC.

Figure S3.19. Disturbance detection method comparison for historic site SC.

Figure S3.20. Disturbance detection method comparison for historic site SCQ.

Figure S3.21. Disturbance detection method comparison for historic site SH.

Figure S3.22. Disturbance detection method comparison for old-growth site VA011.

Figure S3.23. Disturbance detection method comparison for old-growth site VA017.

Figure S3.24. Disturbance detection method comparison for old-growth site VA029.

Figure S3.25. Disturbance detection method comparison for old-growth site VA037.

Figure S3.26. Disturbance detection method comparison for historic site WBQ.

Figure S3.27. Disturbance detection method comparison for historic site ZH.

Sample Depth and Disturbance Frequency

We randomly selected 5, 10, 20, 30, and 44 (actual sample size) trees at MP, the site with the most trees, and summed the number of release events from each draw. The relationship between number of trees and number of releases is important to note, because if one group has more trees than another, this could lead to more releases. We then calculated the number of trees over the pre-1750 period and over the post 1750-period, to assess whether the periods had an even number of trees. A random selection of trees from MP, the site with the most trees sampled (n=44), demonstrated that increasing the number of trees selected for sampling corresponded with an increase in the frequency of releases recorded (Fig. S3.28).

Figure S3.28. Randomly selected 5, 10, 20, 30, and 44 (actual sample size) trees at MP, the site with the most trees, and the number of release events from each sample size.

Actual and Resampled Disturbance Events

Figures S3.29 – S3.54 show by site comparisons of actual (top) and bootstrapped releases using mid-canopy growth averaging (MGA) disturbance detection. 95% confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plots.

Figure S3.29. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.30. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.31. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.32. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.33. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.34. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.35. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.36. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.37. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.38. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.39. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.40. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.41. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.42. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.43. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.44. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.45. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.46. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.47. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.48. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.49. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.50. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.51. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.52. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.53. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Figure S3.54. Comparison of actual (top) and bootstrapped releases (bottom) using mid-canopy growth averaging (MGA) disturbance detection. Confidence limits for bootstrapped releases are indicated by vertical grey bars in the bottom plot.

Combined Bootstrapped Release Events

Figure S3.55. Historic bootstrapped releases by site (top), showing span of each site chronology, and sum of releases each year (bottom).

Figure S3.56. Old-growth bootstrapped releases by site (top), showing span of each site chronology, and sum of releases each year (bottom).

Figure S3.57. Total number of bootstrap releases per year by all sites for historic (top) and old growth (bottom) sites during the common period 1620-1887.

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Chapter 3: Logs from historic buildings provide a reliable carbon isotope record during the pre-industrial period.

Kristen K. de Graauw

ABSTRACT

Decades of research on the physiological response of trees to increasing atmospheric CO₂ (C_a) have yielded conflicting results, as some studies suggest increasing C_a has led to increased intrinsic water-use efficiency (iWUE) in C₃ plants while others suggest the influence of water availability has been underestimated. It has become increasingly important to disentangle the environmental drivers of water-use efficiency and tree growth to ensure accurate predictions of future vegetation response to increasing C_a. Few studies use old living trees (>150 years) to investigate how tree growth and iWUE have changed from pre-to-post industrialization. Here, I compare $\Delta^{13}\text{C}$ tree-ring records exclusively from the pre-industrial period (pre-1850 CE) and post-industrial period (post-1850 CE) to determine if archaeological timbers logs from historic buildings provide a reliable carbon isotope record relative to modern live trees from the same site. Mean $\Delta^{13}\text{C}$ is similar for historic and modern samples ($F_{1,14} = 0.002$, $p > 0.05$), and it is more positive in wet years (19.82‰, 95% CI [19.47, 20.17]) relative to dry years (19.24‰, 95% CI [18.73, 19.75]) ($F_{1,14} = 4.928$, $p \leq 0.05$) (Figure 5), which indicates that historic and modern trees discriminate more against atmospheric ^{13}C (favoring the lighter ^{12}C) in wet years when they are less water stressed. These $\Delta^{13}\text{C}$ results suggest historic wood archives are a reliable tree-ring isotope source for tracking environmental changes of the past several centuries.

INTRODUCTION

The physiological response of trees to increasing atmospheric CO₂ (C_a) is a critical factor in estimating the global carbon cycle, as C_a concentrations have continued to increase following industrialization (IPCC, 2013). Decades of research on the response of trees to increasing C_a yield conflicting results generating uncertainty about the accuracy of ecosystem and climate models (LaMarche *et al.*, 1984; Waterhouse *et al.*, 2004; Peñuelas *et al.*, 2011; Frank *et al.*, 2015; Levesque *et al.*, 2017). Numerous studies compare intrinsic water-use efficiency (iWUE), the rate of carbon uptake to water loss, and growth of trees spatially and temporally to understand tree responses to increasing C_a in different environmental settings (*e.g.* Leonardi *et al.*, 2012; Battipaglia *et al.*, 2013; Levesque *et al.*, 2014; Fernandez-de-Una *et al.*, 2015; Frank *et al.*, 2015; Kwak *et al.*, 2016). Some studies indicate that increasing C_a has led to increased iWUE in C₃ plants (Saurer *et al.*, 2004; Keenan *et al.*, 2013; Tognetti *et al.*, 2014). Others suggest that the influence of C_a on iWUE has been overemphasized, while the influence of other variables, such as water availability, have been underestimated (*e.g.* Silva & Horwath, 2013; Belmecheri *et al.*, 2014; Levesque *et al.*, 2017). Most research captures changes exclusively during the post-industrial period (last 100 years), though a few studies use old living trees (>150 years) to investigate how tree growth and iWUE have changed from pre-to-post industrialization (*e.g.* Feng, 1999; Gagen *et al.*, 2011; Urrutia-Jalabert *et al.*, 2015; van der Sleen *et al.*, 2015; Wu *et al.*, 2015; Giammarchi *et al.*, 2017; Li *et al.*, 2017). It is increasingly important to disentangle the effects of multiple variables that may influence iWUE to reduce uncertainties in vegetation response to increasing C_a which has implications for the both the carbon cycle and soil moisture.

Carbon stable isotopes in tree rings provide a record of annual CO₂ uptake, stomatal conductance, and iWUE over time (Farquhar *et al.*, 1982; McCarroll & Loader, 2004). Generally, when there is more C_a, C₃ plants discriminate more against ¹³C (preferring the lighter ¹²C) (Farquhar *et al.*, 1989). Thus, when there is less C_a, C₃ plants discriminate less, which is reflected in a greater amount of ¹³C. Water-use efficiency is driven by a combination of incoming carbon dioxide (photosynthesis) and outgoing water (transpiration), and both processes are regulated through stomatal conductance (Farquhar *et al.*, 1989). During the photosynthetic process, plants take in C_a and release water vapor through their stomata. Generally, when water availability is low, stomata close to reduce water loss and iWUE increases, which indicates a tradeoff between incoming CO₂ and outgoing water. These relationships suggest that variation in moisture availability over time, in addition to changes in C_a, might influence iWUE and growth of trees.

Major shifts in climate occurred over the last ~1000 years in eastern North America, including the Little Ice Age (LIA; c. 1400–1700 CE), a period marked by cold and dry conditions in the northern Hemisphere (Esper *et al.*, 2002; Cook *et al.*, 2010; Marlon *et al.*, 2017). Temperatures began to increase around 1700 CE, marking the end of the LIA (Marlon *et al.*, 2017; Neukom *et al.*, 2019). Moisture began to increase between 1700 and 1800 CE and has continued to increase to present (McEwan *et al.*, 2011; Pederson *et al.*, 2013; Marlon *et al.*, 2017). Trees of the LIA may have responded to lower moisture by increasing stomatal closure to limit transpiration, thus improving iWUE. This drought response has been found in modern C₃ plants (Leavitt, 1993; Zhang *et al.*, 1997), and demonstrates that in some environments, drought stress supersedes the effects of increasing C_a (Andreu-Hayles *et al.*, 2011; Peñuelas *et al.*, 2011; Levesque *et al.*, 2014; Levesque *et al.*, 2017). However, there was less C_a during the pre-industrial period, which may

have alternatively led to increased stomatal conductance (more open stomata) as a strategy for trees to increase CO₂ uptake, thus resulting in a decrease in iWUE (Overdieck, 1989; Gerhart & Ward, 2010), despite drought conditions. One way to understand the influence of water availability on iWUE of trees is to hold C_a constant. Theoretically, if C_a is constant, any changes in iWUE should be attributed to changes in moisture. Thus, trees that grew prior to anthropogenic C_a provide a real-world scenario in which to study the influence of water availability on iWUE when C_a is relatively constant.

In eastern North America, old-growth forests are often restricted to dry, rocky, and steep slopes due to past logging (Therrell & Stahle, 1998), whereas logs from historic buildings represent fertile upland forests (de Graauw, 2017; de Graauw & Hessel, *in press*) and may provide a complementary isotopic record to inform our understanding of changing drivers of iWUE and tree growth. While isotope records have been recovered from archaeological charcoal (e.g. Hall *et al.*, 2008; Masi *et al.*, 2013), to my knowledge, no studies have used tree-ring data from historic log buildings to provide isotopic evidence of tree iWUE and tree growth prior to industrialization (c. 1500–1850 CE). Before studies of iWUE and tree growth can be conducted using logs from buildings, it is important to determine whether wood archives have undergone wood component degradation to determine and if they yield carbon isotope results consistent with those from modern trees (van Bergen & Poole, 2002). Here, I compare a tree-ring record exclusively from the pre-industrial period (pre-1850 CE) with a tree-ring record exclusively from the post-industrial period (post-1850 CE) to determine if archaeological timbers from the pre-industrial period (logs from historic buildings) provide a reliable carbon isotope record relative to modern live trees (post-industrial period) from the same site. I compare mean $\Delta^{13}\text{C}$ between dry and wet years from each period (historic log building vs modern forest) to test the hypothesis that historic logs and modern trees exhibit similar variability in $\Delta^{13}\text{C}$ between dry and wet years and demonstrate the potential of archaeological timbers as complementary tree-ring isotope sources for tracking changes in iWUE over time.

METHODS

Study Area

The study site is located in the central Appalachian Mountains of eastern North America (Figure 1). This region is part of the Ridge and Valley physiographic province and is characterized by humid continental climate with a mean temperature of 1.7 °C in January and 23.9 °C in July and mean annual precipitation of 101.6 mm (NCEI, 2019). This area is part of the mesophytic Appalachian oak section of the eastern deciduous forest and common species include *Quercus* spp. (oaks), *Pinus* spp. (pines), *Liriodendron tulipifera* (tulip poplar), *Fagus grandifolia* (beech), and *Acer* spp. (maples) (Braun, 1950; Dyer, 2006). The site is in a narrow riparian valley along Strait Creek in Highland County, Virginia (Figure 2) with Derroc cobbly loam soils and sedimentary parent materials (Soil Survey Staff, 2019). One historic log building and one adjacent stand of live trees, ~100 m from the log building, were selected for the study to represent the same location and two different time periods (pre-1850 and post-1850). The historic log building was constructed circa 1840 (de Graauw & Hessel, *in press*) and the modern forest stand grew in an abandoned agricultural field sometime in the 1930s to 1940s.

Tree-ring Dating & PDSI: Dry & Wet Years

For tree-ring dating purposes, I collected 15 ‘A’ core samples from individual *Quercus alba* (white oak) logs in the historic log building using a 14 mm hollow drill bit and 10 ‘A’ cores from live *Quercus alba* trees using a 5 mm increment borer. For seven historic logs and eight live trees, I collected a secondary ‘B’ core for isotopic analysis. I cleaned the drill bit and borer with 100 percent acetone after each sample was collected to reduce the risk of cross-contamination between samples. I used the following standard tree-ring dating practices to crossdate all historic log and live tree samples (Speer, 2010). All ‘A’ core samples were sanded using progressively finer sanding grit for identification of annual ring boundaries. Historic and live tree samples for isotopic analysis (‘B’ cores) were surfaced using a razor. All rings of all samples (‘A’ and ‘B’ cores) were measured and crossdated internally (series against series within a site) before external crossdating against local tree-ring chronologies from the International Tree Ring Data Bank (ITRDB). I then standardized the historic and modern ‘A’ core tree-ring chronologies for further analyses. I used tree-ring reconstructed Palmer Drought Severity Index (PDSI) from the North American Drought Atlas (NADA; grid point 247) (Cook *et al.*, 2004; Cook *et al.*, 2010) to identify the percentile rank of the wettest and driest years during the span of each tree-ring chronology and reconstructed PDSI (1679–2003).

Isotopic Analysis

I selected four of the seven historic ‘B’ samples and four of the eight modern ‘B’ samples for isotopic analysis, based on the condition of the samples (*e.g.* not broken, no anomalous growth). I manually separated the whole rings (earlywood and latewood together) from each historic and modern ‘B’ core using a scalpel and coarsely chopped the rings into smaller slivers, which were placed in small labeled vials (core number and year) with three stainless steel beads. I used a Mini-Beadbeater-Plus (Biospec Products, OK) to grind annual rings into dust and to homogenize the samples so that further analyses represented wood from the entire annual ring. I weighed out 0.400 to 0.600 mg of each sample, added it to a tin capsule, and dried samples in an oven for ~24 hours. I then re-weighed each dry sample and noted the dry wood weight. A Costech IV EA device with a Thermo Delta V Advantage gas isotope ratio mass spectrometer was used to measure $\delta^{13}\text{C}$ relative VPDB and carbon percentage for each historic and modern sample in the WVU IsoBioGem Laboratory.

I calculated carbon discrimination ($\Delta^{13}\text{C}$) from $\delta^{13}\text{C}$ using the following equation:

$$\Delta^{13}\text{C} \approx \text{atmospheric } \delta^{13}\text{C} - \text{plant } \delta^{13}\text{C},$$

and using the standard atmospheric $\delta^{13}\text{C}$ value for the historic period (-6.4‰) (McCarroll *et al.*, 2009) and recorded values over the modern period (-7.3‰ to -8.2‰) (McCarroll & Loader, 2004; Graven *et al.*, 2017).

I calculated the intercellular CO_2 mole fraction (C_i) using the following equation (O’Leary, 1988):

$$C_i = C_a ((\Delta^{13}\text{C} - a)/(b - a)),$$

where C_a is atmospheric CO_2 (ppm), a is external fractionation (4‰), b is internal fractionation (27‰), and $\Delta^{13}\text{C}$ is carbon discrimination (O’Leary, 1988). The fraction C_i/C_a provides stomatal conductance with values close to 1 representing open stomata. C_a values were obtained from

merged ice core data (for historic period) (MacFarling Meure *et al.*, 2006) and direct observations at Mauna Loa and the South Pole (for modern period) (Keeling *et al.*, 2001; http://scrippsco2.ucsd.edu/data/atmospheric_co2).

The atmospheric $\delta^{13}\text{C}$ and C_a data sources used here correct for the Suess effect, the decrease in $\delta^{13}\text{C}$ in plants along with the decrease in $\delta^{13}\text{C}$ of C_a as a result of anthropogenic activity (*e.g.* fossil fuel burning, deforestation) since industrialization (Keeling, 1979; McCarroll & Loader, 2004) and provide a merged record of C_a that fully covered the entire study period (historic and modern periods).

Statistical Analyses

I used the Shapiro-Wilk test to determine if each dataset is normally distributed (Table 1). I used Pearson's Product-Moment Correlation to determine if the entire historic and modern standardized ring-width chronologies are correlated with PDSI, and Welch's two-sample t-test to determine if PDSI is different between entire historic versus modern periods. I used ANOVA to compare variability in $\Delta^{13}\text{C}$ between 'site types' (historic vs modern) and 'PDSI types' (dry vs wet years). Results are reported with 95% confidence limits. For all statistical analyses, $p \leq 0.05$ is considered statistically significant, and $p \leq 0.001$ indicates highly significant results.

RESULTS

Tree-ring Chronologies & PDSI

The historic log building tree-ring chronology spans 1679 to 1840 CE with a mean series length of 144.2 years and the modern stand tree-ring chronology spans 1954 to 2018 CE with a mean series length of 58.3 years. Series intercorrelations (a measure of crossdating strength) from 'A' and 'B' chronologies at each site (Table 2), are similar for the historic site (*mean* = 0.517) and the modern site (*mean* = 0.597) ($p > 0.05$). PDSI is correlated with the standardized historic and modern tree-ring chronologies (Figure 3). Top dry and wet years at each site are reported in Table 3. Overall mean PDSI is comparable for the historic period and the modern period (Table 4) however, PDSI is statistically different between dry years (1748, 1999) (-3.52, 95% CI [-8.39, 1.35]) versus wet years (1725, 2003) (3.70, 95% CI [3.12, 4.28]) (Table 4).

Carbon Isotopes, Discrimination, & Stomatal Conductance (C_i/C_a)

Over the entire study period, C_a increased from 276.71 ppm in 1724 to 375.41 ppm in 2003. $\delta^{13}\text{C}$ values of historic samples range from -27.20‰ to -24.56‰ (Table 5) and modern sample $\delta^{13}\text{C}$ values range from -28.42‰ to -26.13‰ (Table 6). Mean $\Delta^{13}\text{C}$ is comparable for historic and modern samples (Figure 4). Mean $\Delta^{13}\text{C}$ is more positive during wet years versus dry years (Figure 5), which indicates that historic and modern trees discriminate more against ^{13}C (favoring the lighter ^{12}C) in wet years when they are less water stressed. C_i is significantly higher at the modern site versus the historic site (Figure 6), though there is no difference in mean C_i/C_a of historic versus modern samples (Figure 7).

DISCUSSION

The purpose of this study was to determine if logs from historic buildings were reliable sources of tree-ring carbon isotopes during the pre-industrial period. I hypothesized that historic logs and modern trees would exhibit similar variability in $\Delta^{13}\text{C}$ between dry and wet years. Analyses of variance between the historic and modern periods suggest that there are not significant

differences between the two periods, but that trees at both site types respond similarly to dry and wet conditions, despite significant differences in atmospheric CO₂. Overall, these results demonstrate that logs from historic buildings provide a complementary tree-ring isotope sources for tracking changes in $\Delta^{13}\text{C}$, and thus iWUE, over time.

Carbon Discrimination ($\Delta^{13}\text{C}$) in Historic & Modern Periods

After correcting for the Seuss effect, there were no significant differences in $\Delta^{13}\text{C}$ of historic and modern periods. Despite growing under different carbon concentrations (~276 ppm in historic period vs ~375 ppm in modern period), both historic logs and modern trees responded to dry and wet conditions similarly. Trees at both site types preferentially discriminated against ^{13}C (favoring the lighter ^{12}C) in wet years (when they were less water stressed) versus dry years, which is consistent with previous research on the relationship between $\delta^{13}\text{C}$ and drought, where well-watered trees have higher discrimination than trees exposed to drought conditions (Leavitt, 1993; Zhang *et al.*, 1997).

Stomatal Conductance (C_i/C_a) in Historic & Modern Periods

There is no difference in mean C_i/C_a between the historic and modern periods. Higher stomatal conductance has been observed during the pre-industrial period when C_a was lower (Gerhart & Ward, 2010). Overdieck (1989) found that plants growing prior to industrialization were less water-efficient (had greater water loss) than modern plants because they had higher stomatal conductance (stomata were more open) as a response to lower C_a . The similarity in historic and modern C_i/C_a reported here is surprising because C_a in the modern period is higher than in the historic period, therefore higher stomatal conductance during the historic period might be expected. Ehleringer and Cerling (1995) suggest that stomatal reduction is a mechanism for maintaining constant C_i/C_a when C_a is increasing, and numerous species have demonstrated stomatal reduction as a response to increasing C_a (e.g. Woodward & Bazzaz, 1988; Penuelas & Matamala, 1990). It is possible that in the relatively short amount of time between growth of historic and modern trees in this study, modern trees have reduced their stomatal density to maintain constant C_i/C_a as well.

Historic Logs as Dendroisotopic Records

This study, an exploration of the use of historic logs as dendroisotopic records, was met with several challenges. Sectioning annual rings of samples was difficult, as the wood was dry, dense, and composed of tightly suppressed rings versus the wide rings and moist wood of modern samples. It is suggested to avoid suppressed rings when conducting isotopic analyses to ensure annual rings are precisely sectioned (McCarroll & Loader, 2004). Grinding of the dry, dense wood from historic samples also took considerably longer than grinding of modern samples and required smaller slivers of wood to be effective. Further, the study site is located in a riparian valley, which likely influenced the historic and modern tree responses to drought conditions. *Quercus alba* has a deep root system (Burns & Honkala, 1990) and is an anisohydric species, meaning stomatal conductance remains relatively constant even during drought conditions (Meinzer *et al.*, 2013). Thus, severe droughts during both periods likely did not initiate a strong stomatal response in the trees. Despite the relative drought-insensitivity of the site, I still found evidence of similar historic and modern tree responses to dry and wet conditions. Future research should include more drought-prone sites and isohydric species for comparison (e.g. Levesque *et al.*, 2017).

CONCLUSIONS

Conflicting results on the relationship between increasing C_a , $iWUE$, and tree growth have created uncertainty about how future forests will respond to further increases in atmospheric CO_2 (LaMarche *et al.*, 1984; Waterhouse *et al.*, 2004; Peñuelas *et al.*, 2011; Frank *et al.*, 2015; Levesque *et al.*, 2017). Little research has been conducted on these effects in the Appalachian Mountain region of eastern North America, where some of the largest tracts of broadleaf forests (and thus carbon sinks) are located (but see Mathias & Thomas, 2018). In this study, I compared $\Delta^{13}C$ of historic and modern samples to determine if archaeological timbers record similar changes in carbon discrimination under different moisture conditions as compared with modern samples from the same site. While there were several challenges in preparing samples for isotopic analysis, the $\Delta^{13}C$ results from few samples suggest the historic wood archives provide a reliable tree-ring carbon isotope record for tracking environmental changes of the last several centuries and may provide information about the timing of physiological changes in trees as a response to increasing atmospheric CO_2 concentrations.

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Table 3. Shapiro-Wilk test for normality.

Dataset	W	p-value
Historic CRN	0.989	0.263
Modern CRN	0.989	0.924
All Years PDSI	0.998	0.987
PDSI	0.778	0.068
$\delta^{13}\text{C}$	0.975	0.916
$\Delta^{13}\text{C}$	0.954	0.549
Ci	0.859	0.012
Ci/Ca	0.954	0.549

Table 4. Tree-ring dating information, including series intercorrelations (Series IC) for historic and modern tree-ring sites. Cores indicate cores collected for dating purposes (A) and for isotopic analysis (B). Error flags are assigned to 50-year periods of low correlation which may suggest dating errors or anomalous growth.

Site Type	Cores	Trees	Span	Series IC	Flags
Historic	A	15	1679-1840	0.558	3
	B	4	1685-1840	0.475	4
Modern	A	10	1954-2018	0.578	0
	B	4	1952-2018	0.616	0

Table 5. PDSI top drought versus wet years (indicated by PDSI percent rank) for the historic and modern sites.

Site	Year	PDSI % Rank	Dry vs Wet
Historic	1725	99.6%	Wet
	1748	0.3%	Dry
Modern	1999	2.2%	Dry
	2003	100%	Wet

Table 6. Comparison of PDSI values during the historic and modern periods and during dry and wet years of both periods combined.

Data	F statistic	Df	p-value
Historic vs. Modern	0.007	1	0.941
Dry vs. Wet	349.600	1	0.003

Table 7. Carbon isotope values ($\delta^{13}\text{C}\%$ relative VPDB) during the historic period.

YEA	RCE104B	RCN105B	RCN209B	RCS103
R	B			
1725	-25.61	-26.23	-26.31	-26.77
1748	-24.56	-26.47	-25.81	-25.75

Table 8. Carbon isotope values ($\delta^{13}\text{C}\%$ relative VPDB) during the modern period.

YEAR	RCF07B	RCF04B	RCF03B	RCF02B
1999	-27.48	-26.83	-26.84	-27.81
2003	-27.96	-27.46	-28.42	-27.64

Figure 6. Location of the historic and modern site in Virginia, along the West Virginia border.

Figure 7. The study area is located in Highland County, Virginia, just north of the town Monterey. The historic log building is indicated by a star. Strait Creek runs alongside the historic log building and the modern forest site is between the creek and a road, within the circled area.

Figure 8. A graphical comparison and correlations of Palmer Drought Severity Index values (PDSI; blue line) with historic (red) and modern (green) standardized tree-ring chronologies.

Figure 9. Mean $\Delta^{13}\text{C}$ of samples from the historic and modern sites is not significantly different. Black lines indicate the median and boxes indicate the 25th and 75th percentiles.

Figure 10. Variability in $\Delta^{13}\text{C}$ between dry and wet years, shown as percentile ranks and colored by site type. PDSI percentile ranks near 0 indicate dry conditions while ranks near 100 indicate wet conditions. At both the historic and modern site $\Delta^{13}\text{C}$ is more positive during wet years versus dry years. Black lines indicate the median and boxes indicate the 25th and 75th percentiles.

Figure 11. The intercellular CO_2 mole fraction of tree-ring samples, compared by site type (historic vs modern). C_i is significantly higher at the modern site versus the historic site. Black lines indicate the median and boxes indicate the 25th and 75th percentiles.

Figure 12. Stomatal conductance (C_i/C_a) of tree-ring samples, compared by site type (historic vs modern). There is no difference in mean C_i/C_a of historic versus modern samples. Black lines indicate the median and boxes indicate the 25th and 75th percentiles.

Summary

Forests of eastern North America have undergone abrupt transformations over the last several centuries due to changing land use and climate. Scientists and forest managers often rely on old-growth forests as the standard for forest restoration, regardless of the narrow range of site types old-growth forests represent due to past logging. The underlying question of this dissertation is “What information can we obtain from historic logs that old-growth forests cannot offer to ecological research?”. In Chapter 1, I examine the biases and limitations of historic log buildings as archives of past forest ecology, and then explore the use of historic logs to answer ecological questions (Chapters 2 & 3).

Historic log buildings offer a complementary record of past forest ecology and represent a site type that is not often associated with old-growth trees; the upland forest. Despite European immigrants’ bias for species, log sizes, and construction locations, ecological information can be gleaned from historic log buildings. I demonstrate both points in Chapter 2, where I capitalize on the unique site type associated with log buildings and use tree-ring date from these upland forest sites to determine if forests prior to European immigration reflected land use practices of Indigenous Peoples. Recruitment dates, patterns of early growth, and growth releases of historic logs, when compared with old-growth forests, suggest that the depopulation of Indigenous Peoples in the central Appalachian Mountain region led to the establishment of second-growth forests on abandoned land in upland areas.

In Chapter 3, I use carbon isotopes in tree rings from a historic log building and a modern forest stand from the same location to test for differences in the physiological response of trees to moisture and atmospheric CO₂ (C_a) in the pre-industrial (historic) and post-industrial (modern) periods. I hypothesized that historic logs and modern trees would exhibit similar variability in $\Delta^{13}\text{C}$ between dry and wet years. Analyses of variance between the historic and modern periods suggest that there are not significant differences between the two periods, but that trees at both site types respond similarly to dry and wet conditions, despite significant differences in atmospheric CO₂. Overall, these results demonstrate that logs from historic buildings provide a complementary tree-ring isotope sources for tracking changes in $\Delta^{13}\text{C}$, and thus water-use efficiency (iWUE), over time.

Finally, I am eager to see the future of dendro-archaeo-ecology. I have no doubt that scientists more creative than I will ask questions of historic log buildings that offer exciting new pathways to understand the complexity of human-environment interactions. While this research was conducted in the central Appalachian Mountain region of eastern North America using buildings exclusively from the European immigration period (here, ~1600s-1800s CE), it is my hope that the principles are applied more broadly (spatially and temporally) and yield new insights about the human legacy of shaping forested environments.