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Relationships between Climate and Growth of Quercus rubra, Pinus strobus, and Tsuga canadensis in Northern Vermont

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Relationships between Climate and Growth of *Quercus rubra*, *Pinus strobus*, and *Tsuga canadensis* in Northern Vermont

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ABSTRACT

The impacts of climate change on global ecosystems are becoming increasingly clear. Research consistently shows increasing global temperatures are affecting biodiversity, vegetation dynamics, oceans, and important environmental processes. This study examines how climate has influenced tree growth in northern Vermont over the last 100 years for three tree species, *Quercus rubra*, *Pinus strobus*, and *Tsuga canadensis*, in an attempt to understand how these species might respond to expected future shifts in temperature and precipitation. Increment tree cores for these species were collected in Jericho Research Forest and response function analysis was used to examine how temperature and precipitation patterns have affected their growth in this region of Vermont. The importance of precipitation and temperature in driving past growth varied between species. Precipitation only affected *Quercus rubra* growth, with strong positive correlations between growth rates and precipitation in June and July. Temperature was more important to the two conifer species examined (*Pinus strobus* and *Tsuga canadensis*), with the strongest correlations being negative correlations between growth and June temperature. *Tsuga canadensis* growth was also negatively correlated with the temperatures in May, July, and August. These results highlight the importance of diverse species forests in conferring resilience to future climate change, as these represent a range of potential climate responses and sensitivities. Findings indicate *Pinus strobus* and *Tsuga canadensis* may be most vulnerable to changes in future temperature regimes, particularly shifts towards warmer temperatures, whereas *Quercus rubra* demonstrated greater moisture sensitivity. Maintaining mixtures of these and other species may be an effective management strategy for ensuring a wide range of climate responses are present across the landscape. Future work on a wider range of sites and species...
will be critical for expanding the results of this study to the broader landscape of Vermont to inform conservation efforts and identify vulnerable trees species.
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INTRODUCTION

Climate change represents a significant threat to the health and functioning of global ecosystems. The global warming trend developing over the past century (Mann, 2000) has resulted in a distinct shift in the ranges and distributions of many important tree species (Davis & Shaw, 2001). With a wide range of climate conditions and biophysical settings, Vermont provides a unique landscape for a broad mixture of tree species to coexist. Most of these species are adapted to endure harsh winters, but as global temperatures rise, it is expected that suitable habitat conditions for many species will change (Landscape Change Research Group, 2014). There has been a persistent northern shift in the location of optimal climate conditions for Vermont tree species over the past several decades (Davis & Shaw, 2001) with further changes expected over the next century. Growth changes associated with that shift may be reflected in the ring patterns of each tree and can be examined for overall impacts of climate change on a forest ecosystems (Sheppard, 2010). Differences in ring width between different species for the same time period indicates one type of tree grows better than the other during varying climate conditions. This can contribute to determinations of tree species most vulnerable to climate change and predictions of how the structure of Jericho forest will change in the future.

The purpose of this study is to contribute to knowledge of the effects of climate change on tree growth and the variation across different forest conditions. Correlations were examined between long-term climate records and residual chronologies in order to create a current dendroclimatology record for three dominant tree species in Jericho Research Forest. The results from this research will help establish a basis for how different tree species found in Vermont forests might respond to changes in future temperatures and precipitation patterns to gauge
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general vulnerability. This understanding will be useful for information forest conservation efforts focused on increasing the resilience of forests to future changes in climate.

LITERATURE REVIEW

Climate scientists emphasize the need for immediate action against the rise of global temperatures to slow negative effects on the environment (Javeline, Hellmann, Cornejo, & Shufeldt, 2013). The extensive body of literature examining the ecological impacts of climate change suggests that increasing temperatures and changing precipitation patterns will have significant negative consequences for biodiversity (Javeline et al., 2013). Climate change impacts on ecosystems are expected to worsen over time creating a great urgency for the development of strategies to reduce the rate of change and mitigate impacts (Cramer et al., 2001).

There is great uncertainty around how climate change will manifest over the next century making it difficult to predict how specific ecosystems or species will respond to climate change (Cramer et al., 2001). Predicting changes in the distribution of forest habitats is further complicated by the need to account for the fact that each individual species reacts to climate in a separate, unique way (Chuine & Beaubien, 2001). Trees require specific soils and weather patterns to survive, and each species’ range is controlled by patterns in temperature and precipitation (Chuine & Beaubien, 2001). It is expected that warmer temperatures may stress species in northern latitudes given their historic evolution with more moderate temperature regimes; however, the degree of each species’ temperature sensitivity remains an area of great uncertainty (Davis & Shaw, 2001).
Studying the ring patterns of different tree species is one approach for determining how forest stands and growth patterns have responded to changing climate (Manning, Brewer, & Griggs, 2015). Dendrochronology is an important method to analyze and catalogue these changes (Manning et al., 2015). Techniques, such as response function analysis, that relate past patterns in climate to radial increment can be used to determine historic sensitivity of a given tree species to different climate parameters (Zang & Biondi, 2015). This information can be used to gauge general vulnerability of a species and forest ecosystem based on the range of temperature sensitivities that may exist at a site (Janowiak et al., 2018). Jericho Research Forest in northern Vermont is an ideal location to explore these relationships because the area contains five prominent forest types with a wide range of tree species dominating each type (Tursini, 2016). In addition, knowledge of the long-term history of these areas allows for the integration of long-term data collections to understand how the effects of climate change and forest dynamics have affected long-term patterns in growth in these forests. The following sections review relevant literature related to 1) changes in global and Vermont climate regimes, 2) the evolution of Vermont forests over time, 3) projected vulnerability for forests in the region, and 4) theory and methodological considerations in dendrochronological studies. This review is meant to serve as the basis for investigations into climate-growth relationships at Jericho Research Forest.

Global Climate Change

Towards the end of the 20th century, the Earth has experienced a dramatic rise in temperature that is unprecedented when compared to past climate data (Mann, 2000). There are two basic causes of climate change: natural forces that have been recurring for millions of years and anthropogenic forces that have recently developed due to human activities (Thompson,
Natural forces include shifts in the Earth’s orbit around the sun, changes in the atmosphere, changes in the ocean, volcanic eruptions, and periodic variations in energy from the sun (Thompson, 2010). However, the current warming trend over the past 100 years cannot be explained by natural forces (Mann, 2000). A primary cause of anthropogenic-caused climate change is an increase of greenhouse gases in the atmosphere (Javeline et al., 2013). When carbon dioxide is released and enters the atmosphere, it traps infrared energy and warms the planet (Thompson, 2010). Humans contribute to carbon dioxide release through burning fossil fuels, deforestation, agriculture, and decomposing garbage (Thompson, 2010).

Environmental scientists project based on current human activities, as well as a linear rise in temperature, that average global temperatures will increase roughly 3°C this century (Thompson, 2010). In conservative estimates, experts predict an average of 9.5% of species, which would be in the hundreds of thousands, will go extinct in the next 100 years (Javeline et al., 2013). Regional variation among continents translates into more varied localized effects of climate change (Jones, Osborn, & Briffa, 2001), including topographically varied locations, such as Vermont, in the northeastern region of the United States.

**Vermont Climate**

Vermont is a midlatitude state and the climate correspondingly varies annually through warm and cold seasons, resulting in large temperature cycles (Betts, 2011). Mean winter temperatures in northern Vermont from what year to what year range from -5.5°C to -4.4°C each year, and mean summer temperatures in northern Vermont range from 20°C to 22°C each year (Burlington, Vermont Seasonal Average Temperatures, 2016). Snowfall averages between 1800 and 2000 mm in the valleys and up to 2800 mm in the mountains (Morrissey & Sanford, 2016).
Annual precipitation ranges from 870 mm to over 1025 mm in the mountains (Morrissey & Sanford, 2016).

**Climate Change Indicators in Northern Vermont.** Based on local weather station data from Burlington, VT mean winter temperatures have risen about 2.5°C and mean summer temperatures have risen about 1.1°C from 1960-2008 (Betts, 2011). There is some margin for error in this trend due to the high rates of weather variation in northern Vermont from year to year; however, results still show a distinguishable rise in temperature over the past 50 years at a rate higher than regional estimates (Wilmot, 2011) or global estimates of recent temperature increases (Jones et al., 2001).

As annual temperatures rise, the freeze period is reduced in Vermont and amount of snowfall decreases relative to rain (Wilmot, 2011). Less snow cover results in higher absorption rates on the surface of the earth and earlier spring runoff (Betts, 2011). Additionally, precipitation has increased by 15-20% over the last 50 years, as has the frequency of heavy precipitation events (Wilmot, 2011). Air quality deterioration has been expedited in areas where air pollution problems previously existed (Wilmot, 2011). All of these trends resulting from climate change have the potential to negatively impact Vermont forests.

**Vermont Forests**

**Natural History of Vermont Forests.** About 20,000 years ago, the Laurentide Ice Sheet covered Vermont under a mile of ice (Klyza & Trombulak, 1999). Nearly 7,000 years later, the glaciers began to recede and modern Vermont topography started forming (Albers, 2000). As the ice retreated, the glaciers carved out valleys among the Green Mountains (Albers, 2000). A body of water known presently as Lake Champlain expanded and wetlands allowed formation of soils
and new vegetation in areas that now support extensive forests (Albers, 2000). Human inhabitants have also had an impact on the Vermont landscape over many years. Paleoindians settled in Vermont as early as 10,000 years ago, where they contributed to the extinction of large mammals through excessive hunting (Klyza & Trombulak, 1999). The Paleoindians were nomads who traveled across a large range of the landscape (Klyza & Trombulak, 1999). As the years progressed, inhabitants of Vermont began establishing the first permanent villages and agricultural areas (Klyza & Trombulak, 1999).

At the beginning of the 1600s, Europeans settlers arrived in Vermont and throughout the next couple hundred years rapidly spread throughout the state (Klyza & Trombulak, 1999). From the 1600s through the 1800s, Europeans had important roles in shaping the Vermont landscape, as they cleared forests for ranches and timber without consideration for ecosystem conservation (Albers, 2000). By 1900, logging became one of the biggest industries in the state and trees were also cut down to create mining and extraction sites for the collection of slate, granite, marble, and other heavy stones (Albers, 2000). It wasn’t until midway through the 20th century that the people of Vermont started becoming concerned with the environmental impacts of their actions, and reforestation began (Albers, 2000). The landscape history of Vermont has been crucial in the development of the state’s current environmental composition and features.

**Present Vermont Forest Characteristics.** Forests make up about 1.8 million hectares of land in Vermont, or about 73% of the total land (Bechtold, Morin, O'Connell, & Rustad, 2015). The majority of Vermont’s forests are dominated by northern hardwoods, followed by white/red pine, spruce/fir, aspen/birch, and oak/hickory forest types (Bechtold et al., 2015). Jericho Research Forest is a 202.3-hectare area of woodland in Jericho, Vermont owned and managed by the University of Vermont (UVM) that lies between the Champlain Lowlands and Green
Mountain biophysical regions (Tursini, 2016). The university acquired the property in 1941 from the city of Burlington, VT and planted over 70,000 coniferous trees, resulting in a mix of plantations and second-growth forests across the contemporary landscape (Tursini, 2016). A long-term study referred to as the “Farm Woodlot” study was established across the five most common forest types on the forest, including northern hardwoods, white pine, eastern hemlock, and mixed oak-hardwood (Tursini, 2016). The plots were managed in the 1950-1960s and have not received any further treatment since then (Tursini, 2016). These forest types represent a range of potential vulnerabilities to climate, with recent reports suggesting eastern hemlock and white pine may decrease under future climate change, whereas northern red oak may increase (Janowiak et al., 2018)

**Dominant Tree Species in Jericho Forest.** The eastern hemlock (*Tsuga canadensis*) occurs extensively throughout the northeastern region of the United States, and its range also extends south within the Appalachian Mountain range and westward into Michigan and Wisconsin (Ellison, 2014). This foundation species is dominant in many coniferous and mixed-hardwood forests, averages 60 to 70 feet tall, and can live for over 800 years (Carey, 1993). Its regeneration patterns are particularly affected by droughts and fires, and the hemlock prefers moist soils (Carey, 1993). The dense canopy of a full-grown hemlock prevents most light from reaching the forest floor, creating cool soils (Ellison, 2014).

The eastern white pine (*Pinus strobus*) is found along the Atlantic seaboard to New Jersey and down through the Appalachian Mountains (Carey, 1993). When occurring in mixed-hardwood forests, this species is found scattered throughout as a dominant tree towering over other species (Carey, 1993); however, its most common occurrence is often associated with abandoned agricultural fields on which it often forms relatively pure stands (Foster, 1992). The
eastern white pine grows rapidly, successfully colonizes disturbed sites, and commonly reaches 200 years of age (Carey, 1993). It can grow to 150 feet in height and 40 inches in diameter (Natural Resources Conservation Service, 1995). The eastern white grows in a variety of soils, from sandy to heavy textured (NRCS, 1995).

The northern red oak (*Quercus rubra*) is found through much of the eastern United States and southeastern portions of Canada (Tirmenstein, 1991). This oak species can rapidly grow to be 60 to 70 feet tall, and its canopy is able to spread 40 to 60 feet across (Gilman & Watson, 1994). Fire suppression can work against oaks, as lack of forest fires allows the overstory canopy to fill in and gives the advantage to more shade tolerant species, such as maples (Haas & Heske, 2005). However, northern red oak is tolerant to drought and can live in multiple soil types, possibly giving it an advantage in changing climatic conditions (Gilman & Watson, 1994).

**Climate Impacts on Trees in Vermont.** Climate change has many varying impacts on the growth and productivity of trees. Warmer temperatures increase the length of the growing season and may shift the geographic range of certain tree species (Backlund, Janetos, & Schimel, 2008). Evidence has been collected showing distinct range extensions, or “migrations,” of trees in response to temperature changes (Davis & Shaw, 2001). Due to global warming, the entire range of some tree species must be shifted north because the current conditions in which it lives have changed drastically and the area no longer permits optimal tree growth (Davis & Shaw, 2001). As a result of this forced migration, the ranges of suitable habitat conditions for eastern hemlock and eastern white pine are both predicted to have a significant northern shift (Iverson & Prasad, 1998). In addition to latitudinal shifts, there is some evidence that Vermont tree species are moving to higher elevations in some locations (Beckage et al., 2007) and broader
documentation of downslope movement of high elevation species across broader regions (Foster & D’Amato, 2015).

The USDA Forest Service created a model to determine abundance changes in tree species based on the predicted future climate (Landscape Change Research Group, 2014). In the northeastern United States, eastern hemlock and eastern white pine are both predicted to decrease their abundances in their native ranges as climate change worsens (Landscape Change Research Group, 2014). Northern red oak (*Quercus rubra*) is expected to have increased suitable habitat conditions within the United States given the ability of this species to tolerate warmer temperatures and drier conditions relative to more northerly species (Hansen et al., 2001). Red oak’s abundances in its native range are expected to increase as climate change gets worse, as it may be able to take over habitats occupied by tree species decreasing in abundance (Landscape Change Research Group, 2014). If recruitment and dispersal were not limiting, American beech trees in Vermont are expected to be gradually replaced with oak and pine species, which prefer drier conditions (Wilmot, 2011).

Eastern white pine (*Pinus strobus*) has mixed projections in terms of the probability of its suitable habitat type being extensively diminished by climate change (Iverson & Prasad, 2001). One study from Ontario, Canada found that the ability of this species to withstand stress from cold weather in the fall was most closely associated with the mean minimum temperature (Joyce & Rehfeldt, 2013). Other work demonstrated the responsiveness of white pine to moisture and temperature varied depending on localized soil conditions with greater responsiveness to moisture stress on well-drained versus flooded sites (Chhin et al., 2013).

A further effect of the increased length of warm seasons is longer life spans of pests that harm trees and have the ability to spread quickly (Backlund et al., 2008). Increasing temperatures
and shorter winters could improve the survival of these pests, and their attacks will be on trees already vulnerable and stressed from their worsening habitat conditions (Wilmot, 2011). A harmful insect species that will increasingly damage trees as temperatures rise is the hemlock woolly adelgid (Paradis, Elkinton, Hayhoe, & Buonaccorsi, 2008). This invasive insect was introduced to the east coast in the 1950s and has slowly spread, decimating stands of eastern and Carolina hemlock (Paradis et al., 2008). Diseases are another threat to trees as changing climatic conditions impact the lifespan and spread of pathogens. White pine needle damage is an example of a concerning fungal disease that damages and kills the foliage of *Pinus strobus* (Wyka et al., 2017). The presence of this disease in northeastern United States forests is a threat to not only the ecological health of the region, but also the economic value of the lumber industry (Wyka et al., 2017). Eastern white pine is also plagued by several other diseases, including white pine blister rust, red ring rot, root rot, and wood decay (NRCS, 1995).

Climate change increases the risk of drought in certain regions, while it increases extreme precipitation and flooding in others (Karl, Melillo, & Peterson, 2009). Droughts increase occurrences of wildfire and reduce a tree's ability to produce sap (Karl et al., 2009). Higher average temperatures alter winter snowfall, which impacts water availability for trees (Backlund et al., 2008) and increases potential for freezing damage to root systems (Comerford et al., 2013). Additionally, increased concentrations of atmospheric carbon dioxide could stimulate growth for competing tree species or invasive species that can harm native, dominant trees (Backlund et al., 2008). Invasive species, both native and exotic, that thrive quickly when an opening in a forest canopy occurs include hay-scented ferns, buckthorn, and barberry (Wilmot, 2011).

Understanding and studying trees in the context of climate change is important for determining how each of these impacts may affect forest survival in coming years.
Dendrochronology

Dendrochronology is tree-ring dating that has been used as a scientific technique since the early 1900s (Manning et al., 2015). It was discovered by Andrew Ellicott Douglass while he was studying plant growth patterns and their responses to sunlight (Kuniholm, 2001). Most tree species form annual rings whose patterns can indicate environmental and climatic conditions affecting growth (Manning et al., 2015). For dendrochronological studies, each tree ring is measured to examine total ring widths, with earlywood and latewood ring widths also often measured separately (Manning et al., 2015). Earlywood growth correlates with the spring season whereas latewood growth is formed during the summer (Manning et al., 2015). Generally, ring patterns of each individual tree are aggregated and compared to each other to develop a summary of growth for a specific study site or broader region (Manning et al., 2015).

An important step in processing dendrochronological data is cross-dating, which is the comparison of patterns across trees to ensure each ring is dated to its year of formation (Sheppard, 2010). Cross-dating requires a large number of rings in the core samples that can be analyzed for similar widths (Sheppard, 2010). An underlying assumption of this approach is that trees of a single species located in the same area should have similar growth responses to climatic changes and stressor, such as defoliators enabling the rings to be dated (Kuniholm, 2001). This allows for the development of a chronology, or a standardized series of tree rings merged into a single time series (Sheppard, 2010). Most site chronologies consist of at least 20 trees (Sheppard, 2010).

Dendroclimatology. The use of tree rings to reconstruct and describe patterns of growth in relation to climate is often referred to as “dendroclimatology” (Sheppard, 2010). Statistical
models can be used to associate tree rings with climate patterns, most often through precipitation and temperature data (Sheppard, 2010). Years of extreme weather are examined in particular to provide a basis for how ring widths react to sudden changes in their environment (Sheppard, 2010). These dendroclimate model can then be verified using a comparison with climate reconstructed from archives or historical data of climate (Sheppard, 2010). After this validation, the model is evaluated to reconstruct past climate, assuming that the relationship between climate and tree growth is the same today as it was in the past (Sheppard, 2010). This assumption is fairly safe to make as the timeline within which dendroclimate models are evaluated is not long enough for those relationships to change (Sheppard, 2010).

**Factors Affecting Ring Width.** The width of tree rings cannot always be correlated with a single climatic factor. Depending on the tree species, multiple causes contribute to varying tree-ring widths from year to year. Mean monthly precipitation and temperature values for each year are crucial in determining ring width relationships to climate change (Briffa, Osborn, & Schweingruber, 2004). In addition to regional weather patterns like these, local environmental occurrences, such as regular frosts or fires, can have just as much influence on ring widths (Briffa et al., 2004). Some evidence suggests a negative effect of excess ultra violet radiation on photosynthetic processes of trees (Briffa et al., 2004), which may affect tree-ring widths. Conditions during early season growing periods affect initial bud growth and therefore the photosynthetic capabilities of the individual tree (Harold C. Fritts, 1962). Conditions in late season growing periods impact carbohydrate accumulation and reserves for the following year (Harold C. Fritts, 1962). Competition dynamics within a forest stand also influence how successfully each tree species can grow (Briffa et al., 2004). This is accounted for through density measurements of other tree species within a stand surrounding the dominant tree species.
(Briffa et al., 2004). Focusing on mature trees is important in dendrochronology in order to study longer chronologies and collect samples from individual trees that are more accurately representative of the mature population (Briffa et al., 2004). Though this specification ensures more consistent and reliable results, it inserts a bias in that only individual trees with diameters above a certain value have tree core samples taken (Briffa et al., 2004).

**Indicator Years in Crossdating.** There are two ring types that stand out while crossdating as indicators of climate events: false rings and unusually small rings. False rings, or double rings, can be identified by a dark-colored latewood band appearing in the light-colored earlywood of the ring (Stokes & Smiley, 1968). It is important to be aware of false rings because counting one as its own ring would result in the rest of the chronology being off by one year. False rings can be caused by abnormal climate events, like a sudden drought in the middle of the growing season (Stokes & Smiley, 1968). If a false ring occurs during the same year across all or most of a tree species within a stand, this suggests the possibility of a climate event being the cause (Stokes & Smiley, 1968). If the false ring is found only in one or two individual trees, this could be the result of another factor like competition. The production of false rings may be genetic because some trees have more of a tendency to produce them than others (Stokes & Smiley, 1968).

Unusually small rings can be produced be a variety of stresses. Variability in ring widths across a forest stand is highly correlated with variations in precipitation and temperature (H.C. Fritts, 1976). The explanation for a small ring in dendroclimatology can be analyzed by considering the signal-to-noise ratio, where the signal refers to variation due to climatic factors and the noise refers to variation due to non-climatic factors (H.C. Fritts, 1976). Variation due to non-climatic factors include shading by neighbors, lack of soil minerals, size of crown, and tree
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The ring widths in trees highly limited by climatic factors would have a large signal-to-noise ratio (H.C. Fritts, 1976). Rings are also found to be narrower in trees that are crowded (H.C. Fritts, 1976).

**Applications of Dendrochronology.** One of the most important applications of tree-ring dating is the reconstruction of local climate variability (Gegrekirstos, Brauning, Sass-Klassen, & Mbow, 2014). In certain regions of the world, such as Africa, observational climate change data is significantly lacking (Gegrekirstos et al., 2014). Application of dendrochronological techniques in these contexts is vital in filling in gaps in the instrumental record and providing information on how climate has had an impact on vegetation patterns in previous decades. Information added to dendrochronology records in Africa recently include climate reconstruction through the species *Pterocarpus angolensis* in South Africa from 1796 to 1996 (Gegrekirstos et al., 2014). Reconstructions in relation to climate often use information such as temperature, rainfall, river flow, or pressure patterns (Norton & Ogden, 1987).

Another application of studying tree rings is the analysis of plant-water relationships. Climate change is predicted to impact precipitation patterns, which will ultimately affect vegetation growth and distribution (Gegrekirstos et al., 2014). Through information gained from dendrochronology, tree management practices can be implemented and adjusted to fit that region’s needs (Gegrekirstos et al., 2014). Additionally, widths of tree rings can be indicators of atmospheric pollution in an area, as increased carbon dioxide levels have been shown to cause significant declines in tree growth rates (Norton & Ogden, 1987). Examining tree rings can help determine a species’ resilience in the face of environmental disturbances (Norton & Ogden, 1987). By identifying vulnerable plants and vegetation, proactive actions can be taken to try to protect them. The opportunities to use dendrochronology in environmental conservation are
endless and the practice can be widely applied across many disciplines. This study aims to utilize this pertinent technique as a central component to answer the question of how past climate has influenced growth of tree species at the Jericho Research Forest.

MATERIALS AND METHODS

Study Area

The plots for this study were located in the University of Vermont’s Jericho Research Forest, a 202.3-hectare parcel of land in Jericho, Vermont (Figure 1). This land is made up of five dominant forest types that became established by the 1940s. Jericho Research Forest is made up of sloping hills and varied soils. The bedrock is made up of mostly metamorphic rock with sandstone and small amounts of clay (Langlois & Carhart, 2016). The top layers of soil contain glacial till deposited thousands of years ago and alluvium, which is made up of clay, sand, and gravel left behind from rivers. There are also some lake bottom sediments from when Lake Champlain used to spread much farther over the landscape than it does in its current location (Albers, 2000). The forest types that have become established since the university acquired the land are northern hardwood, white pine-red maple, red oak-northern hardwood, hemlock, and pine plantations (Langlois & Carhart, 2016; Figure 2). A few dominant tree species are found across many or all of these forest types. Of these species, eastern white pine (Pinus strobus), eastern hemlock (Tsuga canadensis), and northern red oak (Quercus rubra) were chosen as the focal tree species of this study. These three were chosen to compare species with different physiologies and reactions to climate, according to previous studies. For example, an understory, drought-sensitive conifer like eastern hemlock is expected to react to climate parameters differently than an overstory, drought-tolerant hardwood like northern red oak. Additionally,
reports have predicted abundances of *Q. rubra* to increase and the abundances of the other two species to decrease in their native ranges as a result of climate, making them ideal to compare in this study (Landscape Change Research Group, 2014).

**Figure 1:** A map of Jericho Research Forest with a black rectangle indicating the study site, within which all samples were collected (Vermont Center for Geographic Information, 2018).
Tree Coring

Starting in late June of 2017, 30 increment cores were collected from each of three tree species, *P. strobus*, *T. canadensis*, and *Q. rubra*, and the collection was spread across all forest types in Jericho. These forest types include mixed hardwood, old field pine, pine-hardwood, maple, and beech-oak. Individual trees were selected based on the diameter of the tree at breast height, where the largest trees in the stand were sampled first. The largest trees have the most tree rings available to analyze and provide a longer history. Using 5-mm-diameter increment borers, one core at breast height was collected for each selected tree. This is done by inserting the tip of the borer straight into the tree, then twisting the tool until it is half way through the tree.
trunk and has reached the pith. The core is then carefully pulled out and inserted into a plastic straw for transport (Grissino-Mayer, 2016). Trees were cored perpendicular to the slope to avoid coring through compression wood that grows in response to gravity (Groover, 2016). Methodologies of previous studies suggest when the sample size is 20 or more trees per species in a stand, one core can be taken as opposed to two per tree (Fritts, 1976; Schweingruber, 1988).

Processing the Cores

Increment cores were taken to the laboratory, placed in an oven, and dried for 2-3 days, and then mounted onto wood and sanded to make the ring anatomy clear (Phipps, 1985; Gill, D’Amato, & Fraver, 2016). The cores were first dated visually under a microscope by marking certain years with a pencil. The marking system for dating was as follows: millennia received four dots, centuries received three dots, every 50 years received two dots, and every decade received one dot. As visual dating proceeded, particularly small years and false rings were noted using the list method. Ring widths were measured to the nearest 0.01 mm using a Velmex measuring system (Velmex Inc., Bloomfield, New York) combined with the program “MeasureJ2X.” One core each from Quercus rubra and Tsuga canadensis were removed from the series due to core damage or branches altering the rings and producing unreliable measurements.

Ring measurements and cross-dating were confirmed statistically through COFECHA software (Holmes, 1983). The program COFECHA ensures the quality of the tree ring data and locates errors in dating. The analysis produces series correlation numbers that identify cores that do not match the rest of the series. Any individual core that had a correlation number of 0.5 or below in comparison to the series was analyzed for dating mistakes. Finally, residual
chronologies for each tree species were developed through a method of statistical detrending using the software ARSTAN, or autoregressive standardization (Lamont-Doherty Earth Observatory). ARSTAN standardizes and detrends the tree ring series to form residual chronologies (Holmes, Adams, & Fritts, 1986). It incorporates the cores from all trees sampled of a species into a single chronology for comparison to climate data. The program removes the effects of endogenous stand disturbances and autocorrelation, and produces normalized index values to increase the signal of interest (Holmes, Adams, & Fritts, 1986). This study focused on climate influence on growth and therefore used detrending approaches that removed the influence of changes in tree size (negative exponential) and gap-phase dynamics (cubic splines) on annual ring width.

**Analyses**

Climate data dating back to 1895 was obtained from the PRISM Climate Group (Oregon State University) using the latitude and longitude of the Jericho Research Forest (Northwest Alliance for Computational Science & Engineering, 2018). Specific climate parameters used were monthly precipitation, annual precipitation, and monthly temperature measurements. Minimum, mean, and maximum temperatures for each month were examined. The residual chronologies and monthly climate data were entered into the treeclim software, which is part of the Comprehensive R Archive Network (CRAN). Response-function analysis was applied in treeclim to identify monthly climate variables that have the most influence over a species growth (Zang & Biondi, 2015). Monthly analyses began in June of the previous growth year, as previous year growth in trees contributes to current year growth. Since the climate data dated back to 1895, any years in the residual chronologies before that were not used in this analysis.
Additionally, the analysis was limited to years in which the chronologies contained data from 10 or more tree cores. The cores for *Quercus rubra* all dated back to 1895. Chronologies for the other two tree species started in 1919. Treeclim produced information regarding which years in the chronologies contained strong correlations with the climate parameters using the correlation coefficient $r$. The value of $r$ is between -1 and +1. The closer a correlation is to either of those numbers, the stronger the linear relationship is between the two parameters being compared. Correlations were produced using 0.05 and 0.01 significance levels ($\alpha$). These analyses provide an understanding of differential survival and growth of prominent tree species in response to Vermont’s changing climate.

The total number of correlation tests in this study is 152 per species, which incorporates the analysis of 19 months and testing at two different significance levels. This is important in considering the likelihood of finding a significant result by chance at $\alpha = 0.05$ and $\alpha = 0.01$. These significance levels risk 5% and 1% chances of concluding a significant correlation between the residual chronologies and climate parameters where there is not one, resulting in a Type I statistical error (Dahiru, 2008). Significant correlations that are found at both significance levels or found consistently across all three temperature measurements lend further confidence those correlations were not produced by chance.

**RESULTS**

The initial normalized indices of the residual series master chronologies revealed general trends of tree growth over time. Years with a small amount of growth may be indicators of climate as an influencing factor. The years of least growth for *Quercus rubra*, *Pinus strobus*, and *Tsuga canadensis* respectively were 1909, 1975, and 2003 (Figures 3-5). For *Tsuga canadensis,*
the year 1975 had only a slightly higher index value than 2003, at 0.756 and 0.751 respectively (Table 1). Plotting all chronologies shows common general trends in the growth of the three species since 1919 (Figure 6). Common years between all three species that stand out as low growth years are 1933-1934 and 1949 (Figures 3-5). After 1970, *Pinus strobus* has more extreme high and low growth rates than the other two species. Before 1970, there appears to be a lot more variation in how each of the tree species are reacting to yearly conditions (Figure 6). When linear trendlines were added to each chronology, the slopes remained around zero with little variation, which could be attributed to the detrending methods associated with ARSTAN.

![Figure 3: Master residual chronology of the *Quercus rubra* from 1895 to 2016.](image-url)
Figure 4: Master residual chronology of the *Pinus strobus* from 1919 to 2016.

Figure 5: Master residual chronology of the *Tsuga canadensis* from 1919 to 2016.
Figure 6: Master residual chronologies for Quercus rubra, Pinus strobus, and Tsuga canadensis from the years 1919 to 2016.
The results from the response function analysis also reflect the variation in radial growth across the species. The most significant correlations are those revealed with a 0.01 significance level. For *Quercus rubra*, strong positive correlations were observed between yearly tree growth and precipitation in June and July of the current year, and August of the previous year (Table 1). The June and July precipitation correlations for *Q. rubra* growth were by far the strongest of all correlation results (Table 1). Additionally, this tree species produced a strong negative correlation between tree growth and maximum June temperatures (Table 1).

The yearly tree growth of *Pinus strobus* displayed a strong positive correlation with July precipitation and strong negative correlations with the minimum, mean, and maximum temperatures in June (Table 1). Growth of *Tsuga canadensis* shows a strong negative correlation with precipitation in June of the previous growth year (Table 1). Yearly growth for *T. canadensis* also showed strong negative correlations with the current growth year for mean and maximum temperatures in May and all temperature measurements in June (Table 1). Correlations between mean June temperature and growth for *P. strobus* and *T. canadensis* were the strongest out of all temperature correlations (Table 1).

Looking at the correlations with a 0.05 confidence interval is also valuable for analyzing the climate variables and specific months contributing to tree growth. These correlations are not as strong as those stated above, but still statistically significant. For *Quercus rubra*, tree growth correlated positively with the minimum and mean temperatures of the previous June, and negatively with mean and maximum temperatures of the previous December (Table 1). There was a positive correlation between *Pinus strobus* tree growth and March mean and maximum temperatures (Table 1). Additional significant positive correlations between precipitation and yearly tree growth were found for *Tsuga canadensis* in May, June, and July of the current growth
year (Table 1). Tree growth of this species also showed negative correlations with August and
September of the previous year, and July and August of the current year for at least one
temperature measurement (Table 1). There was also a positive correlation between March
temperatures and growth for *T. canadensis* (Table 1).
Table 1: Relationships between residual chronologies and monthly precipitation, minimum temperature, mean temperature, and maximum temperature based on response function analysis. Months preceded by a “P” represent monthly climate data from the previous growing season. Significant response functions are designated with one asterisk (*) for $p < 0.05$, and two asterisks (**) for $p < 0.01$.

<table>
<thead>
<tr>
<th></th>
<th>Precipitation</th>
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<tr>
<td></td>
<td>PJUN</td>
<td>PAUG</td>
</tr>
<tr>
<td>Q. rubra</td>
<td>+0.050</td>
<td>+0.248**</td>
</tr>
<tr>
<td>P. strobus</td>
<td>-0.128</td>
<td>+0.052</td>
</tr>
<tr>
<td>T. canadensis</td>
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<td>-0.029</td>
</tr>
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<table>
<thead>
<tr>
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<tbody>
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</tr>
<tr>
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</tr>
<tr>
<td>P. strobus</td>
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<table>
<thead>
<tr>
<th></th>
<th>Maximum Temperature</th>
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</tr>
<tr>
<td>Q. rubra</td>
<td>-0.152</td>
</tr>
<tr>
<td>P. strobus</td>
<td>-0.050</td>
</tr>
<tr>
<td>T. canadensis</td>
<td>-0.178*</td>
</tr>
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DISCUSSION

The growth dynamics of the three species examined were highly variable. In a visual examination of the residual chronologies, *P. strobus* appears to be more sensitive to changing conditions over time. Significant extreme climatic events visibly impacted growth patterns of all three tree species. Severe droughts in Vermont occur rarely and usually last for several years at a time (Dupigny-Giroux, 2001). The drought lasting from 1930 to 1936 is evident in the decline in growth for those years in all three chronologies, and *Quercus rubra* shows especially low growth. This is likely due to its reliance on June and July precipitation, as demonstrated in the results of the response function analysis (Table 1). One study suggests red oak species are more vulnerable to drought in dense stands, so changing forest compositions and tree densities in Jericho may affect the stand’s drought tolerance (Moser, 2009). The year 1975 was a very low growth year for all three species. This can be attributed to a large January storm that resulted in record high temperatures around 60 degrees Fahrenheit (National Centers for Environmental Information, 2017). Additionally, the warmer temperatures during a tree’s dormant period may have caused anatomical damage that impacted tree growth for that years and the years to follow. Trees undergo a variety of metabolic and physiological processes during their dormancy to prepare for spring growth, and a large increase in temperature during this time impacts the effectiveness of these processes (Perry, 1971). Storm events and extreme climate events are expected to become more severe and frequent under climate change (Ibarrarán, Ruth, Ahmad, & London, 2007) with these findings suggesting the tree species investigated in this study may be negatively impacted by these changes.

An interesting dynamic appears in the 1990s between all three tree species. During this period, there were synchronous patterns in elevated and reduced growth from 1996 to 2001
Climate-Growth Relationships in Northern Vermont

across the three species. Several significant weather events during this time period that may have contributed to these trends, including was a heavy blizzard in January followed by severe flooding due to precipitation and snowmelt in the spring in 1996 (Ross & Lott, 2003) and a regional ice storm in 1998 with associated large amounts of precipitation and flooding (Dupigny-Giroux, 2000). In the years of the storm events, growth for all three species was high compared to surrounding years. Then, the year directly following the storm event, growth levels dropped significantly. These patterns suggest that extensive rainfall prior to and at the beginning of the current growing season initially benefits tree growth for that year, but has delayed ramifications that impact the next year’s growing season. Although Tsuga canadensis was the only species in this study that showed a significant negative correlation (p < 0.01) with precipitation of the previous year (specifically in June), these trends suggest similar lagged precipitation effects for Pinus strobus and Quercus rubra, particularly when occurring as severe events.

Climate-growth relationships for Quercus rubra in this study were similar to those presented by previous work with this species that covered locations across eastern North America, from Iowa to Maine (LeBlanc & Terrell, 2011). This widespread research found a significant negative correlation between Q. rubra growth and June temperature. The current study produced almost the same correlation, but only for maximum monthly temperatures in June and not minimum or mean temperatures. Multiple studies, in agreement with the current study, found significant positive correlations between Q. rubra growth and June and July precipitation (LeBlanc & Terrell, 2011; Speer, Grissino-Mayer, Orvis, & Greenberg, 2009). The current study found a significant positive correlation (p < 0.01) between Q. rubra growth and August precipitation from the previous growing season, aligning with prior research conducted in the forests of Tennessee, North Carolina, and Georgia (Speer et al., 2009). Adequate
precipitation in the previous year’s growing season allows for more efficient carbohydrate storage, which is used by trees for dormant season processes and to aid the next year’s growth (Loescher, McCamant, & Keller, 1990). These findings highlight the importance of stored carbohydrates in affecting current year growth for the determinate Q. rubra.

Growth for Pinus strobus showed a significant positive correlation (p < 0.01) with July precipitation, which was also found in a study examining this species in northern Minnesota (Kipfmueller, Elliott, Larson, & Salzer, 2010). The negative relationship between white pine growth and June temperature was also observed in other studies of this species (Kipfmueller et al. 2010; Chin et al. 2013), highlighting the potential for reductions in growth if temperatures continue to warm early in the growing season. One of those studies also documented a negative relationship with July mean temperature (Chhin et al., 2013), but that result was not significant in the current study. This difference could be attributed to the focus of the previous study being on P. strobus growth in specific habitats (floodway and terrace forests along a river bank; Chhin et al., 2013).

The climate-growth relationships for Tsuga canadensis in this study were similar to those found in previous work examining this species in Alabama, which is its southern limit (Hart, Gevel, Sakulich, & Grissino-Mayer, 2010). Both studies found a significant positive correlation between T. canadensis growth and May precipitation. Relationships between T. canadensis growth and precipitation in the current study are also comparable to work conducted in the Black Rock Forest in New York (D’Arrigo et al., 2001). Significant positive correlations were found in both studies between T. canadensis and July precipitation, which reinforces the importance of ample moisture during the growing season for this drought sensitive species. Hemlocks have shallow roots that make them especially vulnerable to drought stress compared to the other
species in this study, which both have deeper root systems (Wisconsin Initiative on Climate Change Impacts, 2017). All three monthly temperature measurements for March in the current study show significant positive correlations with *T. canadensis* growth, which was also consistent with the findings of the Black Rock Forest study (D’Arrigo et al., 2001). This could be due to warmer March temperatures melting snow and aiding in earlier photosynthesis (D’Arrigo et al., 2001).

**CONCLUSION**

The evidence presented in this study suggests that of the three tree species sampled, *Pinus strobus* and *Tsuga canadensis* show vulnerabilities to temperature throughout many months of the year. The growth of *T. canadensis* in particular appears to be more consistently hindered by temperatures across seasons. Therefore, these two species are important to monitor as global temperatures continue to increase and humans further alter the environment. Climate change is resulting in traditionally cold months in Vermont to become increasingly warmer, putting pressure on trees to adjust their growing seasons. *Quercus rubra* appears to be most resilient in the face of the changing climate of the species in this study. This species is most reactive to variation in precipitation levels and is able to handle higher quantities of water than the other species due to its larger pores. *Q. rubra* could be negatively impacted as worsening climatic conditions result in more severe natural phenomena, like droughts. All three species have significant relationships with summer months, mainly June and July. Precipitation in these months generally benefits the growth of these trees, while high temperatures hinder them. Diversity of tree species within a forest stand aids the system by increasing its resilience to climate change, which has varying levels of impact on individual tree species as seen in this
study. Forest management practices incorporating diversity focused on species richness should be encouraged.

Further research would need to be completed within Jericho Research Forest to eliminate other contributing factors as the causes of these growth patterns. There are a lot of elements in the northeastern forests of North America that help or hinder tree growth, such as soil quality, competition between trees for nutrients, available sunlight through thick canopies, and disturbance agents like pests and diseases. The disturbance agents would be interesting to study in association with climate parameters, since climate change shortens the frost period in Vermont and allows for more extensive pest and disease damage on trees. When comparing these three species, it is also important to keep in mind that *Quercus rubra* and *Pinus strobus* are often tall, overstory species, while *Tsuga canadensis* can be found in various canopy layers and is highly shade-tolerant. They may react differently to limited resources, different levels of sun exposure, and competition. When strong correlations show up across an entire stand between tree growth and climatic data, some of the factors impacting individual trees can be ruled out.

Any errors in visual dating, such as counting a false ring or not identifying a microring, were compensated through statistical and correlation analyses. This study could be extended by further isolation of climate as the limiting factor for tree growth. Data are available on individual trees from the “Farm Woodlot Study” conducted in the 1950s in Jericho Research Forest. Another research group retagged the trees that were part of this study throughout the summer of 2017. Using these two sets of data, tree densities and crowding could be analyzed to determine how the stand composition has changed over time. This information combined with the residual chronologies can be used to study localized impacts on individual tree growth. There are many opportunities to expand upon and continue this study.
LITERATURE CITED


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