Chapter 1

Introduction

In the Southern Appalachian Mountains, unforested openings known as balds exist on or near some high-elevation peaks, mainly above 1350 meters, in North Carolina, Tennessee, and Virginia. Some of the balds are mainly grassy with only scattered shrubs and trees, while others are dominated by heath (shrubs of the Ericaceae family). Environmental conditions in balds typically include high solar radiation, desiccating winds, high rainfall, frequent fog, and thin rocky soils. Adjacent forests may be composed of red spruce (*Picea rubens*) and Fraser fir (*Abies frasieri*) in the highest elevations or northern red oak (*Quercus rubra*) along with northern hardwoods such as *Betula alleghaniensis, Fagus grandifolia, Aesculus flava;* balds oftentimes serve as transition zones between these forest types.

Both grassy and heath balds contain rare and endemic species and are prized for their contributions to global biodiversity. Over time, they have become cultural landmarks that provide extraordinary scenic vistas of surrounding mountains and recreational havens for those hiking the popular Appalachian Trail. They have also become endangered habitats, receiving the highest ranking of G1 (critically imperiled) in terms of Global Conservation Status, due to heavy recreational use, the introduction of exotic biota, and in the case of grassy balds, succession by forest. The threat of losing grassy balds to trees has created a land management dilemma concerning the status, maintenance, and future of balds. Loss of these balds to ecological succession represents undesired change from a human standpoint and emphasizes the need for more scientific study of ecological patterns and processes that could inform conservation strategies for these unique habitats.

Researchers have sought to explain the origins, existence, and dynamics of balds through a variety of theories including natural succession (Johnson 1888; Camp 1931; Whittaker 1956; Mark 1958), Amerindian occupation (Wells 1938, 1956; Metress 1976), climatic variation (Billings and Mark 1957; Mark 1958; Copenheaver et al. 2004, 2005), fire frequency (Gersmehl 1970; Barden 1978; Knoepp et al. 1998; White and Sutter 1998; White et al. 2001), grazing (Gersmehl 1970; Lindsay and Bratton 1979, 1980; White and Sutter 1998; Johnson 1992; Weigl and Knowles 1995), and disturbance (Barden 1978; Thomas and Pittillo 1987; Sullivan and Pittillo 1988). However, to date, research addressing the role of human land-use change and climate change as a contributing factors in the encroachment of forest into the balds is insufficient. Thus far, scientific investigations have been limited to a handful of balds; expanding analyses to other balds could verify existing theories and possibly help postulate new ones.

Tree encroachment into balds has been detected throughout the southern Appalachians in recent decades (Lindsay and Bratton 1979, 1980; Thomas and Pittillo 1987; Sullivan and Pittillo 1988; Johnson 1992; Copenheaver et al. 2004, 2005). One approach to better understanding the present trend is to reconstruct the temporal and spatial patterns of tree advancement into balds through tree-ring analysis. Tree-ring study (dendrochronology) provides a means to document the timing of tree establishment and recruitment and when combined with spatially explicit methodologies such as belt transects mapped with a Global Positioning System (GPS) can provide high resolution records of historical patterns of tree invasions into balds. Geographic Information Systems (GIS) can be used to help model and visualize such patterns. Tree-rings also allow for the study of past and present climatic variation on annual growth which can shed light on past ecological conditions in a stand (Fritts 1971, 1976; Hughes et al. 1982; Bradley 1985; Heikkinen 1987; Fritts and Swetnam 1989; Cook and Kairiukstis 1990; Fritts 1991;

Tessier et al. 1997; Martineli 2004). This type of analysis can provide information on local, regional, or even hemispheric climatic mechanisms responsible for controlling tree growth in high elevation forest-grass ecotones. Documentation and evaluation of historical patterns and processes can aid in the development of sustainable land management plans aimed at preserving southern Appalachian balds into the future.

Research Objectives

This thesis was motivated by two objectives. The first objective was to use both tree-rings and geographic information systems to reconstruct temporal and spatial patterns of tree encroachment into Craggy Gardens, a southern Appalachian grass/heath bald, and to examine these patterns to evaluate the role of land use history and ecological disturbances as causal factors in vegetation change. The second objective was to use tree-rings records from red oak stands adjacent to Craggy Gardens and Big Bald, another southern Appalachian grass bald, to identify the climate-tree growth relationships in high elevation forest-grass ecotones and evaluate such associations over the past century.

Organization

This chapter (1) is intended to introduce southern Appalachian balds and to briefly discuss the need for environmental reconstructions; in particular tree-ring studies aimed at gaining a better understanding of tree encroachment into southern Appalachians balds. Chapter 2 is a manuscript prepared for submission to *Progress in Physical Geography*. The research reconstructed temporal and spatial patterns of northern red oak (*Quercus rubra* L.) encroachment into Craggy Gardens, NC using dendrochronology, belt transects, GPS, and GIS and determines the casual factors. Chapter 3 is a manuscript prepared for submission to *Canadian Journal of Forest Research*. The research addresses the dendroclimatic response of northern red oak

(*Quercus rubra* L.) growing at its ecological tolerance limit in two southern Appalachian grass and heath balds, Craggy Gardens and Big Bald, and evaluates changes in the climate-tree growth associations over the past century. Chapter 4 includes a summary of the results of this thesis work regarding tree encroachment into southern Appalachian grass/heath balds. Chapter 4 also provides a brief discussion of the current status of dendrochronological research in the southern Appalachian Mountains, and highlights the potential for future research in tree-rings, geographic information systems, and southern Appalachian grass and heath balds.

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Chapter 2

Temporal and Spatial Patterns of Tree Encroachment into a Southern Appalachian Grass/Heath Bald Using Dendrochronology and GIS

C. J. Crawford[1], L.M. Kennedy[1], and C.A. Copenheaver[2]

Department of Geography[1] and Department of Forestry[2], Virginia Polytechnic Institute and State University

Abstract: Craggy Gardens, a southern Appalachian grass/heath bald in western North Carolina is experiencing *Quercus rubra L.* encroachment on the western slope. We used belt transects, dendroecologial analysis, and spatial interpolation in GIS to reconstruct *Q. rubra L.* establishment and recruitment over the past 245 years. Tree rings records from 128 trees yielded distinct spatial and temporal patterns of encroachment mainly explained by disturbance. Historical grazing by European livestock appears to be the main disturbance both suppressing tree establishment during grazing and facilitating tree establishment and recruitment after the cessation of grazing in the early 1930s. A slower rate of tree encroachment after the 1960s is primarily a result of shading after canopy closure after the initial surge of establishment. Inverse weighted distance interpolation proved informative of spatial patterns and supported the reconstruction of temporal patterns through dendrochronology. Cross-validation highlighted spatial uncertainty and error in *Q. rubra L.* prediction of age and showed that a small amount of extreme observations (e.g. tree > 100 years) contributed significantly to error statistics. Inter-annual and decadal climate variation is apparent in *Q. rubra L.* suggesting that a combination of human disturbance and environmental conditions has and continues to govern bald vegetation dynamics. Absence of tree encroachment after 1980 is due to the ecological restoration project aimed at restoring and maintaining Craggy Gardens to promote preservation of rare and endangered species and scenic appeal. This reintroduces human disturbance, which will further alter successional development of the community.

Keywords: **southern Appalachian bald, *Quercus rubra L.*, tree rings, disturbance, grazing, inverse weighted distance, cross-validation**

I Introduction

In recent decades, a number of studies have examined the encroachment of forest into grasslands and theories of bald origins. These investigations have focused primarily on patterns and processes associated with land-use (Lindsay and Bratton, 1979, 1980; Mast et al., 1997), disturbance (Sullivan and Pittillo, 1988; Morgan and Wearne, 200l; Clarke, 2002; Rozas, 2003; Bai et al., 2004), and climatic variation (Copenheaver et al., 2004; Copenheaver et al., 2005). Grassland ecosystems have also received attention in the literature because they support a variety of niches and habitats that are pertinent to the survival of rare and endangered species (Baskin and Baskin, 1988; White and Sutter, 1998).

Specifically in the Southern Appalachian Mountains, unforested high-elevation balds are classified as grass or heath, contain an array of locally rare species, and are prized for their scenic vistas. Grass/heath balds in particular are experiencing a relatively recent upslope shift in the forest boundary that is threatening these isolated communities. The loss of grassland habitat at Craggy Gardens has sparked considerable concern for land managers (Craggy Garden Management Plan). The Nature Conservancy has ranked grass balds as G1, i.e., “Critically Imperiled Globally”. This study is aimed at reconstructing historical patterns of tree encroachment into Craggy Gardens and assessing the possible causal factors.

Issues surrounding the origin, maintenance, and management of grass balds have been vigorously debated within the scientific literature and by land management agencies. Theories of bald origin include Amerindian occupation (Wells, 1938, 1956; Metress, 1976), natural succession (Camp, 1931; Whittaker, 1956), climate fluctuations (Billings and Mark, 1957; Mark, 1958), fire frequency and land clearance (Gersmehl, 1970; Barden, 1978), and grazing (Lindsay and Bratton, 1979, 1980; Johnson, 1992; Weigel and Knowles, 1995). These earlier studies of grass balds were focused on classification and characterization; whereas more recent analyses have concentrated on understanding the roles of land-use, disturbance, and climatic patterns and processes on grass bald vegetation and surrounding forest types. Several studies across a broad range of ecosystems have used historical records, tree-rings, geographic information systems, and aerial photography (Mast et al., 1997; Fensham and Fairfax, 2003; Anderson and Baker, 2005; Fensham et al., 2005; Franco and Morgan, 2007) to evaluate and reconstruct relationships between past land-use, disturbance, and vegetation dynamics demonstrating the utility of an integrative methodology for such investigations.

Oak forests are thought to have been a major component of pre-settlement eastern forests and heavily impacted by Amerindian and European land-uses (Nowacki et al., 1990; Abrams and Copenheaver, 1999; Shumway et al., 2001). Tree-rings are reliable ecological proxies for past land-use, disturbance, succession, and climate and allow for reconstructions of spatial and temporal patterns and processes, specific events, and continuous environmental change (Fritts, 1976; Heikkinen, 1987; Fritts and Swetnam, 1989; Banks, 1991; Abrams et al., 1995). Trees growing at their ecological tolerance limits in high elevation mountain environments can provide robust records of environmental change (Cook et al., 1982; Hughes et al., 1982, Schweingruber et al., 1990; Tessier et al., 1997). Transforming tree-ring data into a geographic information systems dataset can provide opportunities for spatial analysis and visual representation supplementing the tree-ring records. The specific objectives of this study are to 1) reconstruct the temporal and spatial patterns of *Q. rubra L.* establishment and recruitment into Craggy Gardens; 2) uncover potential causal factors for tree encroachment; and 3) determine the utility of this integrative methodology in reconstructing historical forest-grass boundaries in a southern Appalachian grass/heath balds.

II Methods

1 Study Area

Craggy Gardens (1715 m) is located (35° 42' N; 82° 23' W) approximately 30 km northeast of Asheville, North Carolina at milepost 364 on the Blue Ridge Parkway (Figure 1). Craggy Gardens is one of three main peaks comprising the southwest-northeast trending Craggy Mountains, which join the Black Mountains to the north, where the highest peak in the eastern

United States, Mount Mitchell (2040 m) is located. The climate of the study area is characterized as temperate with cool moist summers and cold snowy winters. Yearly rainfall is estimated at 150 cm increasing with elevation (Shanks, 1954). Bedrock is composed of Pre-cambian mica gneiss and schist; soils are thin and rocky (Perkins and Gettys, 1939).

The vegetation at Craggy Gardens is common to both southern Appalachian grass balds and heath balds. Bald species include mountain oat-grass (*Danthonia compressa*) and hair-grass (*Deschampia flexuosa*) along with various forbs. Heath species include purple rhododendron (*Rhododendron catawbiense*), mountain laurel (*Kalmia latifoila*), and high bush blueberry (*Vaccinium corymbosum*). The north, east, and southeast aspects are covered by heath, American beech (*Fagus grandfolia*), yellow birch (*Betula allgenhensis*), and mountain ash (*Sorbus americana*). The summit of Craggy Gardens and the south and southwest aspects are covered mainly by heath, grass, and scattered mountain ash. The west aspect contains an open-grown *Querus rubra* L. woodland with a mixed grass-herbaceous layer and sporadic patches of heath.

Craggy Gardens, like most of the Southern Appalachians has historically experienced major changes in land use through time. In the late 1800s, this area was subjected to widespread logging, livestock grazing, and human-set fire (Pyle, 1988). Historical records are lacking to confirm logging around Craggy Gardens, but evidence of livestock grazing is clear in historical photos at Craggy Gardens Visitor Center on the Blue Ridge Parkway.

2 Tree Ring Data Collection and Preparation

There are three separate contiguous grassy openings within Craggy Gardens that are divided by thick patches of heath. Two of the three openings (the “north” and the “south”) were selected for this study based on the observed successional dynamics of grass to forest (Figure 2). The sampling design was aimed at capturing *Q. rubra L.* encroachment moving upslope from the western slope into Craggy Gardens. We established a baseline in each opening running along the contour of the ridge. Six points were located along the baselines (four in the “north” opening and two in the “south” opening). From each point, we walked a perpendicular path using a compass to the forest-grass boundary. There we began a 5 m-wide belt transect extending downslope (still perpendicular to the baseline) until we reached mature forest. We determined mature forest conditions based on four criteria following Copenheaver et al. (2004): 1) presence of a well developed forest canopy; 2) presence of large mature trees; 3) presence of coarse woody debris; and 4) absence of grass in the understory with a developing leaf litter.

Within each transect, we sampled all *Q. rubra L.* > 2 cm DBH (Diameter at Breast Height). Seedlings and saplings with diameters less than 2 cm were tallied. Trees 2–7 cm DBH were cut at a height of 10 cm using a hand saw. Trees > 7 cm in diameter were cored once using an increment borer at an average height of 25 cm. Coring trees near the ground allows the best opportunity to get accurate establishment dates. Trees > 30 cm DBH were cored twice to bolster sample depth and chronology development. Several *Q. rubra L.* appeared to be very old. Some were either too large for our increment borers or were rotten in a portion of the heart, so we could not retrieve an accurate establishment date. Within the mature forest, we sampled additional *Q. rubra L.* trees to increase sample depth of older trees, and to extend the chronology backwards in time.

Cores were air-dried, mounted, and then sanded with progressively finer grit sandpaper following standard dendrochronological techniques (Phipps, 1985; Stokes and Smiley, 1996). We eliminated five cores from the analysis due to damage. Each core was visually cross-dated using common signature years (Yamaguchi, 1991). Skeleton plotting was also used to date cores with missing rings, cracks, or damage during sampling, and to insure that the oldest trees were dated accurately (Stokes and Smiley 1996). Annual ring-widths for each core were measured to the nearest 0.00l mm using a Velmex Unislide and a Leica Stereozoom microscope. We verified the crossdating using COFECHA (Holmes, 1983).

3 GIS Data Collection and Preparation

We geo-referenced points every 10 m along the belt transect and at endpoints (Figure 2). Forest-grass and forest-heath boundaries were geo-referenced using a Trimble Geo-Explorer to establish current grass/heath bald area. Using the program GPS Pathfinder Finder 3.1, geo-referenced points were converted to point and polygon shapefiles and uploaded into ArcMap 9.1. We obtained a digital raster graphic (DRG) of the Craggy Pinnacle quadrangle from the United States Geological Survey (USGS) and a digital elevation model (DEM) of Buncombe County, North Carolina. We created a point data set by assigning each 10 m interval with the age of the oldest *Q. rubra L.* within the 5 m belt transect. We assumed that the oldest tree in each 10 m section was the first tree to establish. The *Q. rubra* L. point data was then joined to the point shapefile in ArcMap 9.1.

4 Tree-Ring Reconstruction

A total of 128 trees were dated and then analyzed for establishment and recruitment. We assigned the dated trees to their sampled transect and 10 m interval (0–10, 10–20 etc.) ranging from the forest-grass boundary to mature forest. For the six transects, the range of total distance from the forest-grass boundary to mature forest was 140–160 m. To document the relationship between tree age and distance from the forest-grass boundary, all six transects were compared across each 10 m interval to determine the oldest tree at that given interval; the age of that tree would be assigned as the establishment date for that 10 m interval. We used Pearson’s correlation (Copenheaver et al., 2004, Davis, 2002) to examine the relationship between tree age and distance from the forest-grass boundary. Each tree was assigned to an age class ranging five years, and these classes were examined for possible pulses or lags in tree recruitment. *Q. rubra L.* reproduces on a four-year mast cycle, which is important for temporal tree establishment and recruitment (Sork and Bramble, 1993).

5 GIS Reconstruction

We used the geostatistical analyst in the ArcMap 9.1 toolbox. Inverse distance weighted (IDW) interpolation function spatially interpolated *Q. rubra L.* establishment across the grass/heath bald. The extent of the interpolation was based on: 1) belt transect length; 2) natural vegetation boundaries (e.g. heath and heath/forest); and 3) transition in tree species composition associated with aspect (Figure 3). The IDW function assumes that an observation at an unsampled location is a weighted average of its nearest neighbors in a local neighborhood surrounding the unsampled location. IDW is a deterministic exact interpolator that weights predicted observations based on distance from the measured observation. Predicted observations near measured data points are assigned higher weights in the prediction, whereas predicted observations further away from measured data points have smaller weights and less effect on predicted observations (Mueller et al., 2005; Robinson and Metternicht, 2006).

When trees establish ahead of forest-grass ecotone (e.g., balds) boundaries, they expand in island patterns (Figure 4) initially from one tree. Once several trees have established, forest canopy development begins and continues to spread outwards from that initial establishment or otherwise referred to as recruitment. Recruitment is the final phase of forest canopy development, which links all initial island patterns of establishment together resulting in an intact forest canopy. Given that *Q. rubra L.* predominantly reproduces through stump sprouting (Sander, 1990), it was plausible that an IDW interpolation could in fact simulate tree establishment in the grass/heath bald based on the concepts of distance and nearest neighbors in its prediction of *Q. rubra L.* establishment.

Across six transects, there were 107 points with geo-referenced locations; however, only 58 points had known *Q. rubra L.* establishment dates. The other 49 points did not have any trees due to the open-grown structure of the *Q. rubra L.* woodland. Including the locations with no tree data would have contributed considerable error to the interpolation results, so we excluded them from the spatial interpolation. We divided the 58-point dataset into 30 random subsets generated by the ArcMap 9.1 geostatistical analyst, with each subset having 29 calibration points and 29 verification points for cross-validation. Cross validation is a statistical procedure that removes an observation from the prediction dataset and then uses the remaining data to predict a value at the data point which was removed. This procedure was repeated for all observations in the dataset to assess cross-validation. The root mean square error (RSME) was calculated for measured and predicted values to report the prediction error of the IDW function (Mueller et al., 2005).

With each subset, the IDW interpolation function was calculated to the power of two (Mueller et al., 2005) and included a 15 point neighborhood when predicting a raster grid of *Q. rubra L.* establishment age. Using raster calculator in the spatial analyst toolbox in ArcMap 9.1, all grids were combined to obtain a mean and standard deviation raster grid of *Q. rubra L.* establishment age. Both grids were reclassified using manual breaks. We used the mean grid was used to reconstruct *Q. rubra L.* establishment into the grass/heath bald. The standard deviation grid allowed us to 1) assess the interpolation error in its prediction of *Q. rubra L.* establishment; and 2) to identify the level of confidence associated with the IDW interpolation. From the mean grid reconstruction, we developed a time series of maps to spatially represent *Q. rubra L.* encroachment into Craggy Gardens.

III Results

1 Tree-Ring Reconstruction

This analysis revealed two distinct patterns of *Q. rubra L.* establishment (Figure 5). Pearson's correlation revealed an $r = 0.41$, ($p < 0.10$) between tree age and distance from the forest-grass boundary. This result suggests that *Q. rubra L.* age is related to distance from the forest-grass boundary, but does not have a strong dependency with regard to a constant upslope ecotonal movement.

The first pattern of establishment indicates an episodic upslope movement of *Q. rubra L.* between 1760 and 1925 (represented by filled circles, Figure 5). This pattern is reflective of infrequent and patchy establishment of *Q. rubra* L. across the grass/heath bald during this time period. In this case, belt transects inhibited the ability to capture all patches of old trees in a particular area of the grass/heath bald. A second pattern of high establishment is observed from 1925 to 1935 across all intervals and all transects between the present forest-grass boundary and mature forest (Figure 5).

There appear to be three distinct periods of recruitment from 1760 to the present (Figure 6). Although episodic establishment occurs during 1760 to 1925, recruitment is low. After high establishment during 1925 and 1935, a sustained rate of recruitment continues until 1960. After 1960, recruitment declines considerably to a period of no recruitment after 1980. Notably, we found no *Q. rubra* L. seedlings (< 2 cm DBH) in any belt transects; however, a few stump sprouts were present, but were either dying or stunted indicating no potential to further reproduce or reach the forest canopy.

2 GIS Reconstruction

For the IDW mean interpolation (Figure 7), the average calibration RSME across thirty subsets was 13.5, while the average verification RMSE was 13.8. This indicates that on average, the IDW interpolation over-predicted or under-predicted *Q. rubra L.* establishment age by approximately 13 years. The first inclination is to disregard interpolation reliability; however, the standard deviation of the mean interpolation offers a contrasting explanation. Although the IDW interpolation had an error of 13 years, both the calibration and verification average RSME were similar indicating interpolation stability. The standard deviation (Figure 8) showed that the interpolation consistently over-predicted or under-predicted *Q. rubra L.* establishment mostly around the oldest and youngest trees (Figure 7). Since IDW interpolation predicts estimates based on a local neighborhood of points, a lack of sample depth in tree age would create an insufficient number of nearest neighbors from which to predict an observation.

The mean interpolation (Figure 7) with all 58 points provided a spatial representation of establishment and recruitment after 1925 (Figure 9). Before 1925, *Q. rubra* L. establishment was gradual and sporadic; however, after 1925, *Q. rubra L.* establishment accelerated with a peak period during 1935-1955. From 1955-1965, *Q. rubra L.* establishment declined with limited establishment after the late 1960s. There were several *Q. rubra L.* recorded in the 1970s, but the mean interpolation over 30 subsets filtered trees in low abundance.

IV Discussion

1 Tree-Ring Reconstruction

Our dendrochronological analysis of *Q. rubra L.* showed that from 1760 to 1925, trees established episodically moving upslope from the west into grassy areas. *Q. rubra L.* encroachment is confined to the western slope at Craggy Gardens mainly due the presence of barrier heath species on all other slopes. *Rhododendron catawbinense* is known to significantly inhibit tree establishment due to heavy shading and high density (Nielsen et al., 2001; White et al., 2001). Even so, Thomas and Pittillo (1987) found that American beech have invaded the southeastern slope of Craggy Gardens and were establishing in heath at steady rates mainly facilitated by sprouting.

Our analysis was not aimed at detecting evidence of fire; however, heath balds are considered fire-climax communities that result from disturbance (White et al., 2001). Several studies reveal that *Q. rubra L.* establishment and recruitment in the eastern U.S. significantly increased after European settlement due to logging and widespread fire (Abrams and Copenheaver, 1999; Abrams et al., 1997; Nowacki et al., 1990; Copenheaver et al., 2004), and throughout most of the Southern Appalachians (Pyle, 1988). Knoepp et al., (1998) found evidence of past fires at three grass balds in Tennessee through analysis of soil charcoal. Conversely, Craggy Gardens has relatively high rainfall due to its elevation and position in the southern Appalachians, where it receives abundant Atlantic moisture. This moist environment would likely not support frequent natural fires, although natural fires may be possible under extreme drought conditions. Human-ignited fires in the mid to late 1800s were possible and even documented in the Black Mountains to the northeast (Pyle, 1988).

Historical photos from interpretive plaques on the Blue Ridge Parkway provide evidence that Craggy Gardens was grazed in the late 1800s and early 1900s. The dramatic increase in *Q. rubra L.* establishment times closely with the cessation of grazing at Craggy Gardens, when the land was procured by the government by at least the early 1930s. Establishment of trees in the absence of grazing is in agreement with Lindsay and Bratton (1979, 1980), who found that tree establishment within Gregory and Andrews balds was strongly correlated with the cessation of livestock grazing around the 1935. Weigel and Knowles (1995) have proposed grazing by megaherbivores (such as bison and later replaced by European sheep, goats, and cattle) as important factors in bald maintenance.

A pronounced spike in *Q. rubra L.* recruitment at Craggy Gardens between 1935 and 1960 likely indicates an absence or decline in human disturbance, which would have promoted natural succession and development of a partially closed *Q. rubra L.* canopy. This results is in keeping with several studies (Barden, 1978; Lindsay and Bratton, 1979, 1980; Sullivan and Pittillo, 1988; Johnson, 1992) which have predicted that without an adequate disturbance regime, grass balds would succeed from grass to shrub followed by forest canopy development.

The semi-closed canopy that existed by the mid 1960s would have caused a decline in *Q. rubra L.* recruitment due to shading of the understory. A lack of sunlight is known to negatively affect seedling establishment (Nielsen et al., 2001; Clarke, 2002). In this case, *Q. rubra L.* seedlings would have experienced decreased light availability and competition with a mixed grass-herbaceous layer. Moisture availability also limits tree seedling establishment (Nielsen et al., 2001; Clarke, 2002). Mature *Q. rubra L.* are drought tolerant, however, seedlings are more sensitive (Abrams, 1990**;** Abrams et al., 1997; Fekelugen et al., 2002); *Q. rubra L.* may have continued to reproduce, but seedlings may have been out-competed by grass species. At higher latitudes, studies of *Q. rubra L.* show that climate variability plays an important role in *Q. rubra L.* growth releases, suppression, and recruitment, especially in event years (Abrams et al., 1997; Fekelugen et al., 2002, Tardiff and Conciatori, 2006; Tardif et al., 2006). Specifically, Gramulich (1993), Pederson et al., (2004), and Copenheaver et al., (2005) found that temperature gradients are important in controlling local and regional northern hardwood ecotones.

2 GIS Reconstruction

The main source of error in the mean interpolation (Figure 7) of *Q. rubra L.* establishment age were points containing trees greater than 75 years of age and younger than 40 years of age. The standard deviation (Figure 8) of the mean interpolation further highlighted this fact showing that *Q. rubra L.* age was highly variable around a few points. Muller et al. (2005) suggest that disproportionate interpolation weights are allocated to extreme observations and can contribute considerable impact on cross-validation error statistics. This was the case in our study with a average RMSE of 13 years across both calibration and verification points.

The reconstruction (Figure 9) using IDW corroborates the tree-ring reconstruction supporting the idea that grazing was the main factor responsible for maintaining the grassy areas of Craggy Gardens and suppressing tree establishment before 1925. After 1925, increased *Q. rubra L.* establishment suggest cessation of grazing, which times closely with the acquisition of Craggy Gardens by the government (Figure 9). After 1935, there was accelerated and continuous *Q. rubra L.* establishment and recruitment resulting from an absence of disturbance and favoring successional development (Figure 9).

From the early 1960s to the present, the reconstructed pattern of establishment showed dramatic decline with no apparent establishment after the 1970s. At this point, the tree-ring and GIS reconstructions diverge slightly in their results; however, further examination of the tree-ring records suggest that *Q. rubra L.* recorded in the 1970s was most likely a result of recruitment within the closing *Q. rubra L.* canopy. Regardless, both reconstructions point towards a significant decline in *Q. rubra L.* establishment and recruitment in recent decades. It is evident that both the cross-dated *Q. rubra L.* tree-ring records and spatial interpolation of such records are in agreement and support similar historical patterns of *Q. rubra L.* encroachment into Craggy Gardens (Figures 5,6,9).

3 Tree-Rings and GIS Methodology

The approach of using IDW interpolation to map the patterns of tree encroachment into Craggy Gardens through time should serve as a supplement to the more robust high resolution tree-ring data. This GIS analysis should not be considered as introducing error into the tree-ring record, but a mere spatial representation to support temporal data. Conversely, this integrative approach has yielded analogous results regarding *Q. rubra L.* encroachment into Craggy Gardens. We have found no studies integrating these techniques; however, several others have compared the effectiveness of using IDW interpolations versus kriging interpolations (Mueller et al., 2004), mapping soil properties (Robinson and Metternicht, 2006), and mapping invasive species (Roberts et al., 2004). Each study highlighted the importance of cross-validation and error assessment as method for testing interpolation results.

In our study, testing for validity of results provided insights on error and possible improvements in methodological approaches for tree-rings and spatial interpolation. We recommend that if spatial interpolation is a main goal of the investigation, a sufficient set of data points should be collected across space in grid format to establish an adequate neighborhood for estimation of tree age. On the other hand, avoidance of error may not be possible unless there is normal distribution of tree age in the sampling grid and should be considered in future applications of this methodology.

4 Conclusion

The western slope of Craggy Gardens was considerably larger in grass area before the early 1900s indicated by the remnant grass understory present in the *Q. rubra L.* woodland. Until the early 1900s, *Q. rubra L.* establishment was probably limited by grazing and browsing of buffalo, elk, and deer, which gave way to intensive livestock grazing and browsing upon European settlement (Figure 10). With the cessation of grazing by the early 1930s, rapid *Q. rubra L.* establishment occurred with continual recruitment until the mid 1960s in a relatively undisturbed community. Shaded understory conditions under a closing *Q. rubra L.* canopy in the mid 1960s resulted in a decline in establishment and recruitment. Absence of establishment and recruitment after 1980 can be explained by the ecological restoration project enacted at Craggy Gardens in 2001, which seeks to restore the grass bald by cutting trees and mowing (Figure 10). Present management represents a new human disturbance regime aimed at preserving rare and endangered species and the scenic appeal of the grassy bald at Craggy Gardens. Climate variability is evident in *Q. rubra L.* from Craggy Gardens based on inter-annual and decadal ring structure found sequentially in all the cores. These patterns of variable growth suggest that climate may have initiated and synchronized growth throughout the entire establishment of the *Q. rubra L.* Further research on climate-growth relationships in *Q. rubra* L. will help us to better predict how future climate change will govern *Q. rubra L.* growth along with human activities.

This integrative approach to reconstructing tree encroachment into southern Appalachian grass and heath balds has provided valuable information on the temporal and spatial patterns of past land-use and disturbance and their influences on ecological processes in a southern Appalachian bald. It also provided evidence to expand on the ideas of spatial interpolation and spatial uncertainty associated with the quantification of error in model prediction. This integrative methodology could also be strengthened with repeat aerial photography, which could help to corroborate the tree-ring records and spatial interpolation techniques. This type of analysis could be applied to other southern Appalachian balds in order to provide land management agencies with highly accurate historical evidence of past conditions. Such studies could in form management plans focused on preserving scenic vistas, and rare and endangered species.

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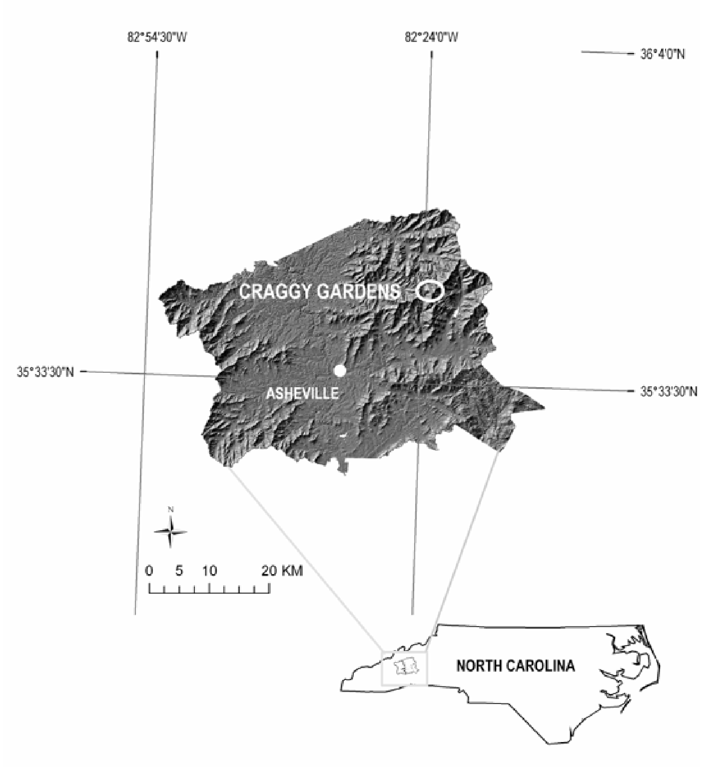

Figure 1. Craggy Gardens in the southern Appalachians of western North Carolina. Craggy Gardens and Asheville are located in Buncombe County, North Carolina. Craggy Gardens (1715 m) is northeast of Asheville on the Blue Ridge Parkway (30 km).

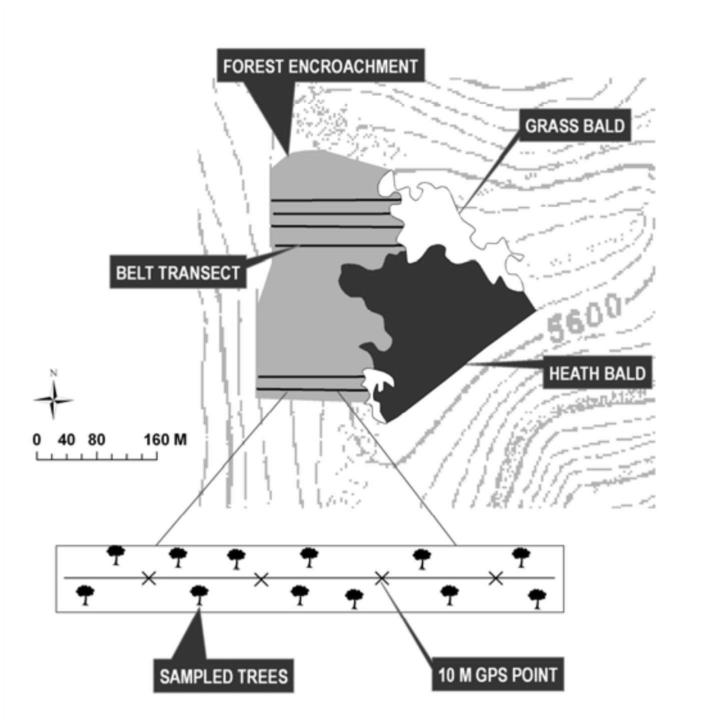

Figure 2. Craggy Gardens study site with vegetation types and 5 m–wide belt transect locations shown. Basemap is a 1:24,000 topographic quadrangle with a contour interval of 20 ft.

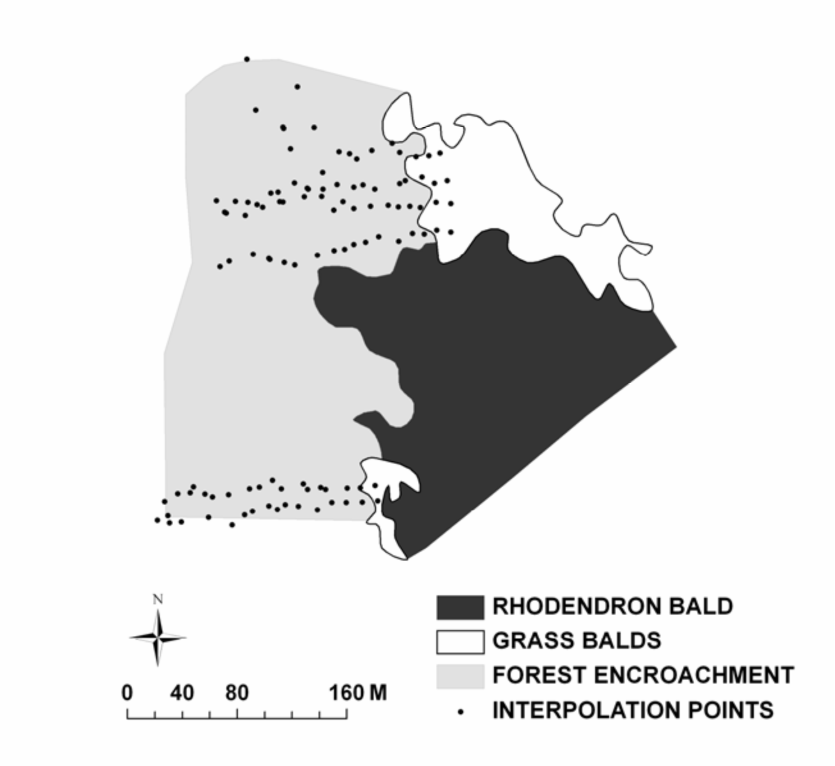

Figure 3. *Q. rubra* L. point dataset used for the IDW spatial interpolation. Each black circle represents the oldest *Q. rubra* L. tree (n = 58) at each 10 m interval used in the IDW interpolation. The geo-referenced points have a 5 m range of accuracy within the actual location. This explains the variability in point locations on each transect.

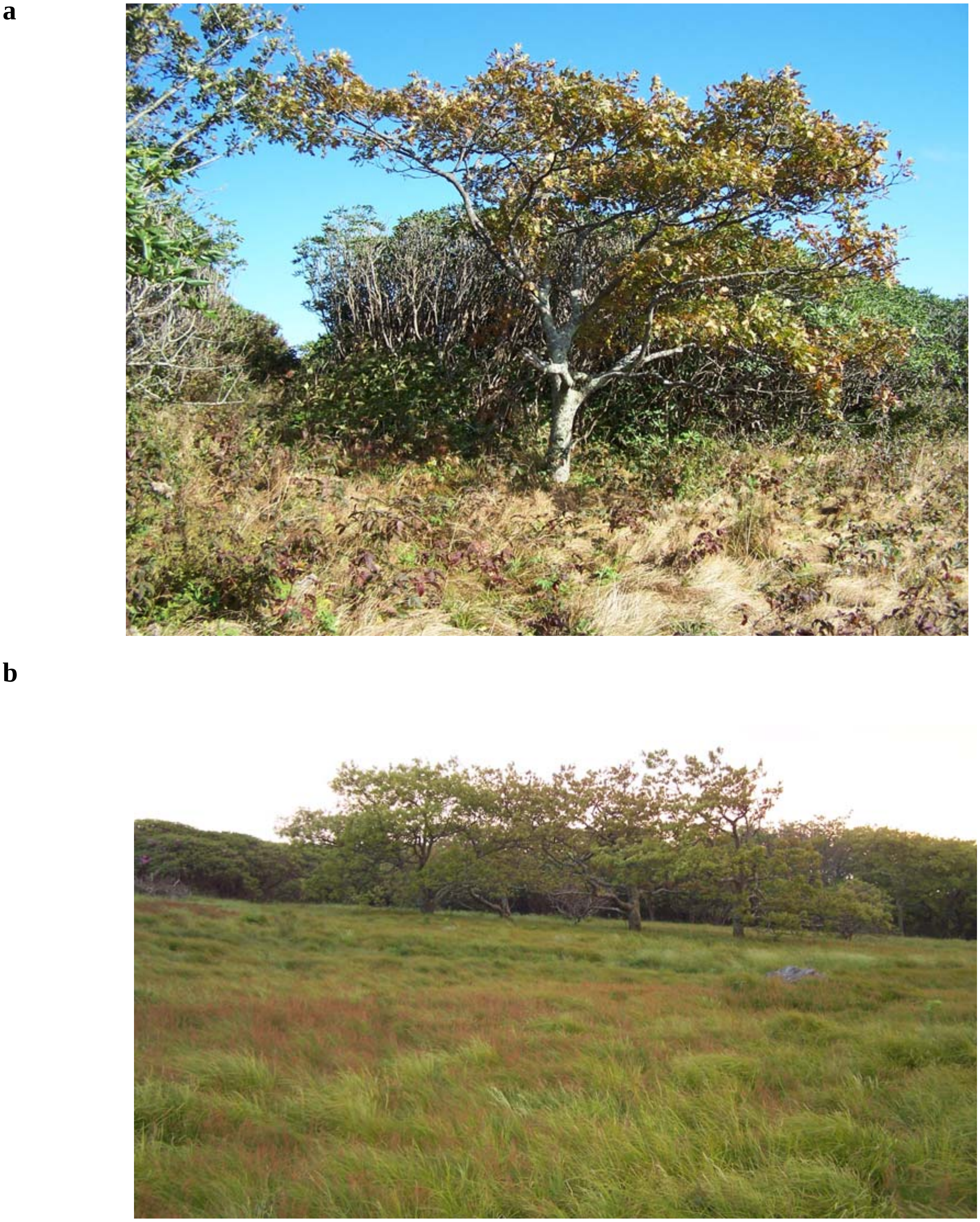

Figure 4. *Quercus rubra* L. establishment and recruitment into Craggy Gardens. a) Initial individual tree establishment; b) Island pattern expansion of tree establishment.

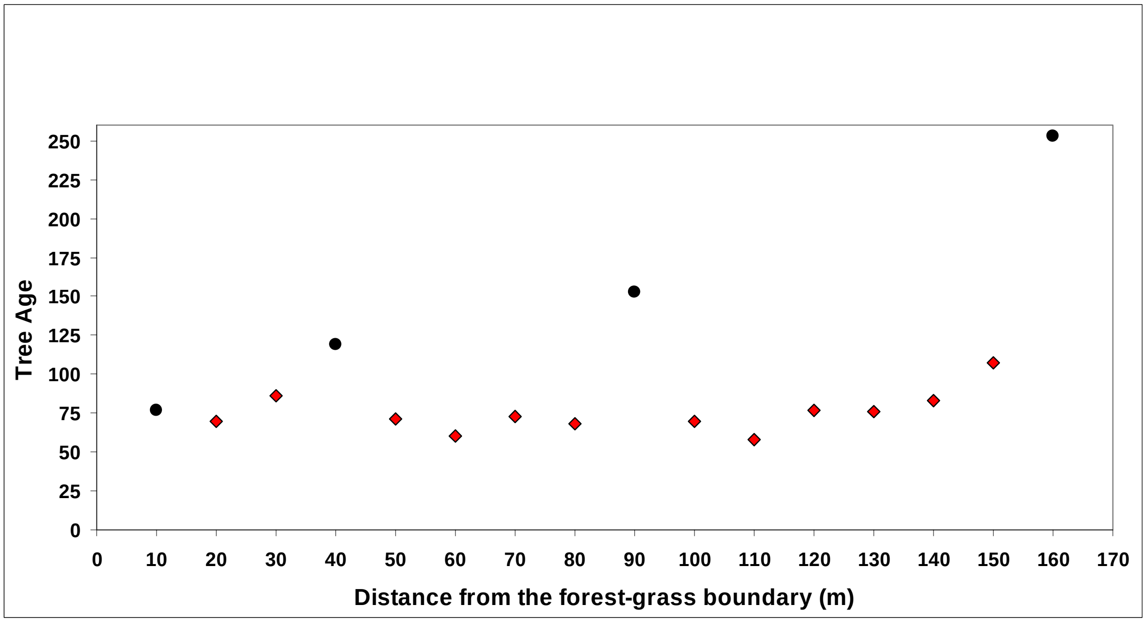

Figure 5. Relationship between *Q. rubra* L. tree ages and distance from the forest-grass boundary at Craggy Gardens $r = 0.41$ ($p < 0.10$). Filled circles represent the age trends found with gradual encroachment of trees into the grass/heath bald before 1925. Diamonds show rapid encroachment during 1925-1955.Each individual point indicates the oldest *Q. rubra* L. found within any 10 m interval of all transect data combined. Distance from the forest-grass boundary is moving away from the grass bald toward mature forest.

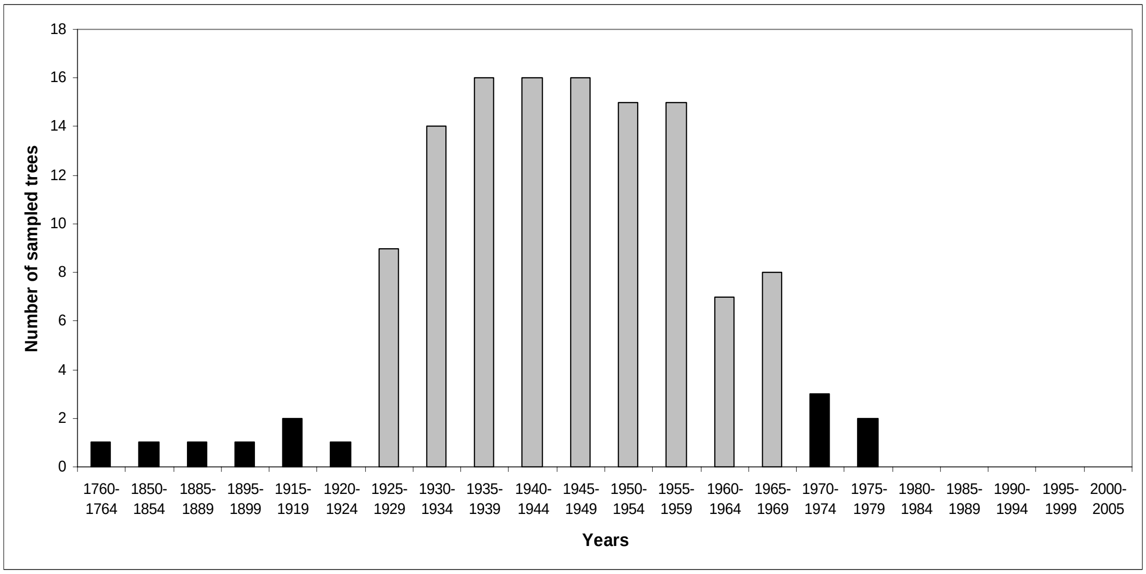

Figure 6. *Q. rubra* L. recruitment at Craggy Gardens. Blacks bars indicate the total number of trees recruited in each five-year period (all transects combined). Gray bars represent years with exceptionally high recruitment.

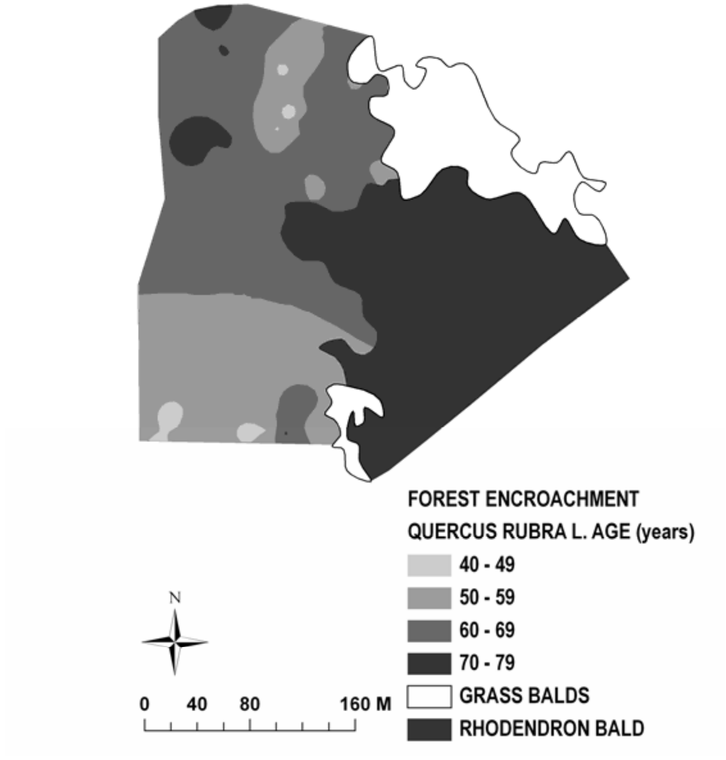

Figure 7. The mean interpolation age of *Q. rubra* L. establishment based on 30 random subsets where 29 points were used for calibration and 29 points were used for verification in the IDW interpolation (e.g.. cross-validation).

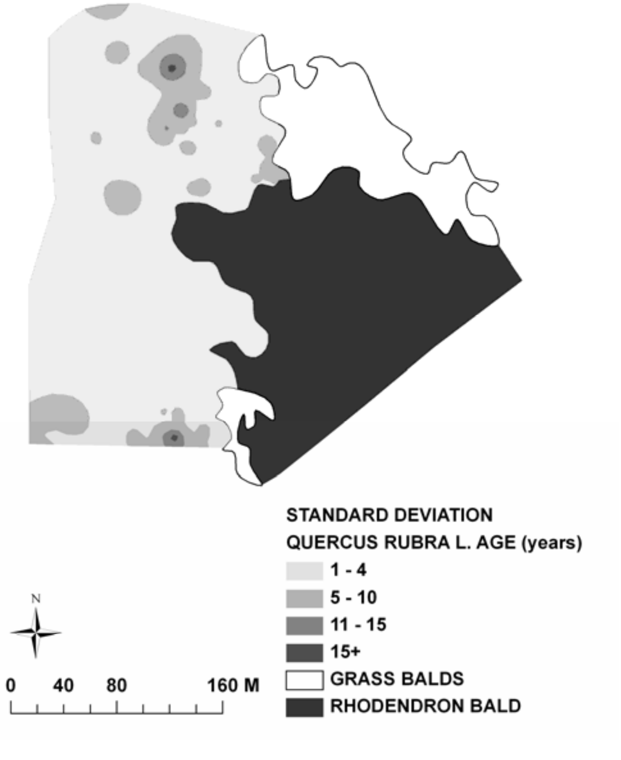

Figure 8. Standard deviations of *Q. rubra* L. establishment age derived from the IDW interpolation highlights the error in *Q. rubra* L. establishment age. The IDW cross-validated interpolation consistently over-predicted and under-predicted *Q. rubra* L. establishment age approximately 13 years.

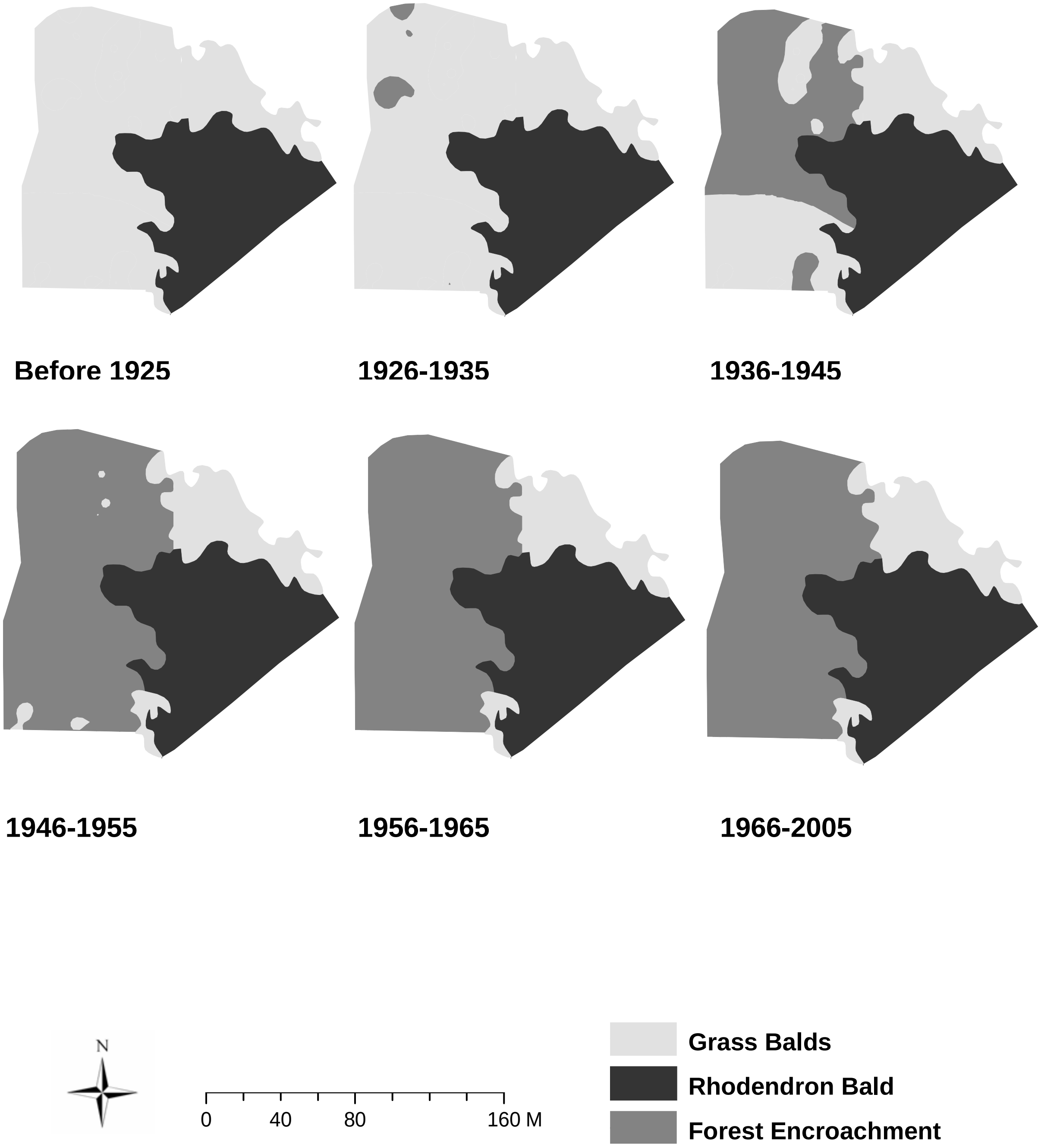

Figure 9. A reconstruction of *Q. rubra* L. encroachment on the western slope of Craggy Gardens since 1760 A.D

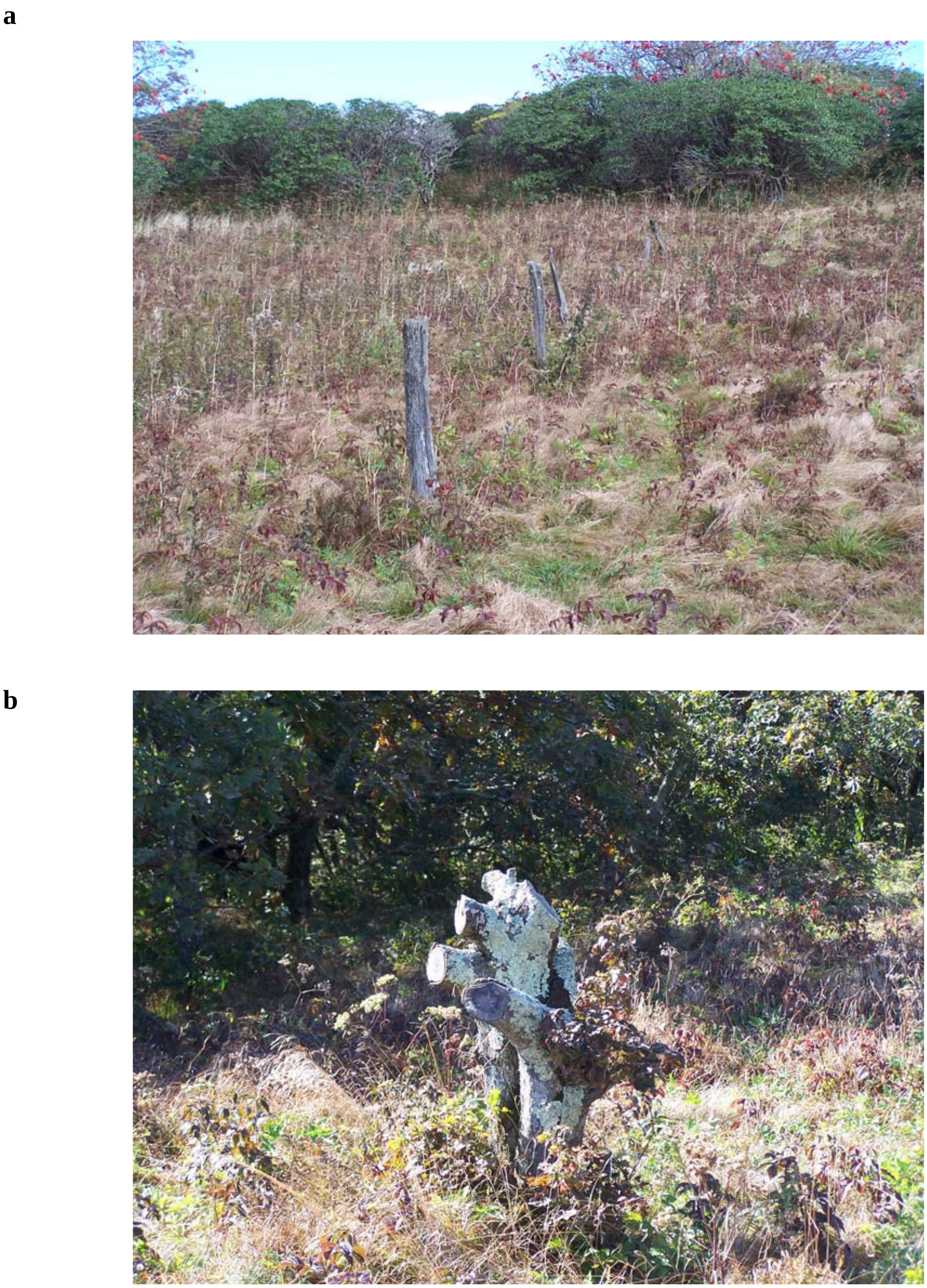

Figure 10. Evidence of past and present land-use at Craggy Gardens. a) Remnant fence post from livestock grazing. b) Cutting and removing trees in the grassy bald under the ecological restoration plan at Craggy Gardens.

Chapter 3

Assessing the Dendroclimatic Response of Northern Red Oak (*Quercus rubra* L.) Growing at its Elevational Tolerance Range, in the Southern Appalachians

C. J. Crawford[1], L.M. Kennedy[1], and C.A. Copenheaver[2]

Department of Geography[1] and Department of Forestry[2], Virginia Polytechnic Institute and State University

Abstract: Two high elevation northern red oak (*Q. rubra L.*) chronologies indicate that *Q. rubra L.* regionally cross-date (r = 0.60) reflecting a common climate forcing. Bootstrap correlation and response functions showed a significant positive response to previous year's May-June temperature and negative response to June PDSI. Moving window regression revealed a slight reduction in time-stable responses to early growing season temperature in recent decades; a July temperature signal in the current growing season was identified after 1970. Documented periodic and episodic droughts over the 20th century in both chronologies affected temperature signal stability in *Q. rubra L.* Split-period calibrations for ring-width and temperature using multiple stepwise regressions were developed to predict annual ring-width from independently withheld temperature data. Calibration and verification results suggest that extending the temperature/ring-width calibration intervals yields a reduction in explained variance due to water availability-*Q. rubra L.* ring-width associations. In most cases, temperature models overestimated and/or underestimated ring-width during known drought years. Our main conclusions included the following: 1) *Q. rubra L.* radial growth at its elevational tolerance limit is highly dependent on early growing season temperature and to a lesser degree water availability. 2) A time-stable spring temperature signal can be observed, but is affected by the frequency of drought conditions; and 3) Detection of a significant summer temperature signal after 1970 suggests a increased sensitivity to warming temperatures and possible ongoing shift in *Q. rubra L.* climate-tree growth associations in recent decades.

Keywords: **southern Appalachians, *Q. rubra L.*, dendroclimatology, climate-tree growth associations, moving window regression, time-stable climate signals**

Introduction

With mounting natural proxy evidence for recent warming trends (Mann et al. 1999; Briffa 2000), and questions of forest ecosystem response to climate change, it is imperative to continually evaluate the effects of climate variability on biological and ecophysical processes of trees growing near and at their ecotonal margins (Cook and Cole 1991; Foster and LeBlanc 1993; Loehle and LeBlanc 1996; Loehle 2000; LeBlanc and Terrell 2001; Tardif et al. 2001;

Iverson et al. 2004; Pederson et al. 2004; Tardif et al. 2006). Both elevational and latitudinal forest boundaries have proven useful in investigations of climate-tree growth associations due to the principle of limiting factors (Fritts 1976; Jacobi and Tainter 1988; Gramulich 1993; Loehle 2000; LeBlanc and Terrell 2001; Tardif et al. 2001; Pederson et al. 2004; Tardif et al. 2006). Trees growing in these transition zones can offer robust records of climatic sensitivity through annual ring formation of growth following dormancy and provide valuable time series with embedded long- and short-term frequencies (Fritts 1976). Expanding tree-ring chronology networks across these boundaries is paramount to further understanding tree growth-climate responses, and/or possible shifts in such time dependent sequences (Biondi 2000; Solberg et al. 2002; Wilson and Elling 2004; Wilson et al. 2004; Buntgen et al. 2006; Carrer and Urbinati 2006). The main objective of this paper is to apply well-replicated methods in dendroclimatology to such transitional zones in the high elevations of the southern Appalachians where chronology development is lacking.

Tree-rings have proven invaluable when reconstructing historical trends in climate at northern hemispheric (Briffa et al. 1998a; Mann et al. 1998), continental (Fritts 1991; Cook et al. 1999), regional (Cook et al. 1998; Wilson and Luckman 2003) and local scales (Druckenbrod et al. 2003). In eastern North America, where long records are limited because temperate forest lifespans rarely surpass two centuries (Fritts 1976) and human disturbance is widespread (Abrams et al. 1995; Nowacki et al. 1990; Abrams et al. 1997) substantial time series development would contribute needed chronology information (Martineli 2004). Although reconstructions of past climate in eastern and southeastern North America do exist (Stahle et al. 1988; Stahle and Cleveland 1992; Stahle et al. 1998) historical and recent temperature changes in the temperate high elevations of the southern Appalachians are less well documented.

In the southern Appalachians, high elevation forest openings known as balds sustain a variety of grasses, sedges, and heath species. These balds result from a combination of factors (Wells 1956; Whittaker 1956; Billings and Mark 1957; Mark 1958; Weigl and Knowles 1995, White et al. 2001), but have recently been experiencing forest closure over the past 75 years (Lindsay and Bratton 1979; Sullivan and Pittillo 1988; Copenheaver et al. 2005; 2004; Crawford 2007). These deciduous forest-grass ecotones have been identified as potential sites to find remnant forest spanning three centuries in age (Copenheaver et al. 2004). The vegetation cover in the treeless balds and adjacent forest are partially to fully open-grown woodlands with a persistent grass-herbaceous layer. This forest structure is rare compared to most eastern temperate forests, where a closed canopy mixed stratum is the standard (Fritts 1976; Cook and Kariuisktis 1990). Rock outcrops, thin soils, and exposure often provide stressful site conditions for the establishment and perpetuation of deciduous forest species such as northern hardwoods in and around balds (Petty and Getty 1939). Stressful growing conditions along with open canopies in woodlands allows for potential longer term climate signals in forest-grass ecotones not influenced by classic closed-canopy growth suppression and release (Fritts 1976; Hughes et al. 1982; Bradley 1985; Cook and Kariuisktis 1990).

Longer lived temperate forest species such as *Querus* have been studied extensively with respect to dendroclimatology and have proven their utility, contributing significant understanding to tree growth-climate associations (Tainter et al. 1984; Jacobi and Tainter 1988; Tainter et al. 1990; Foster and LeBlanc 1993; Gramulich 1993; Pan et al. 1997; Rubino and McCarthy 2000; LeBlanc and Terrell 2001; Garcia-Gonzalez and Eckstein 2003; Pederson et al. 2004; Tardif and Conciatori 2006a; Tardif and Conciatori 2006b; Tardif et al. 2006). *Quercus spp*. have also been used for fire frequency, ecological, and human disturbance reconstructions demonstrating its importance as a proxy on both pre and post-European timescales in eastern North America (Shumway et al. 2001; Abrams et al. 1995). Remnant *Q. rubra L.* growing in sensitive mountain environments (Tessier et al. 1997) such as in balds and surrounding forest provide opportunities to advance hypotheses regarding *Q. rubra L.* response to climate and its usefulness in evaluating past and present variation. The specific objectives of this investigation were to *i*) develop high elevation *Q. rubra L.* chronologies in southern Appalachian sites *ii*) identify the climatic response of *Q. rubra L.* growing at its elevational distribution limit *iii*) compare the tree growth-climate response of chronologies from two different sites at similar elevations 35 km apart in different mountain ranges, and *iv*) evaluate whether climate signals are time-stable over the past century.

Methods

Study Area

The study sites, Craggy Gardens and Big Bald, are located in western North Carolina at (35° 42' N; 82° 23' W) and (35º 59' N, 82º 29' W), respectively (Fig. 1). Craggy Gardens resides on the Blue Ridge Parkway approximately 12 km northeast of Asheville. Craggy Gardens (1715 m) is part of the Great Craggy Mountains that trend northeasterly joining the Black Mountains to the northeast. Big Bald is located in the Pisgah National Forest on the North Carolina-Tennessee state line, roughly 47 km northwest of Asheville. Big Bald (1681 m) is part of the Bald Mountains that also trend northeasterly. Big Bald is approximately 35 km northwest of Craggy Gardens (Fig. 1).

Both sites experience analogous climate conditions year round where cool moist summers and cold snowy winters are persistent. Average July temperatures range from 27º C (max.) to 14º C (min.) and January range 8º C (max.) to -6º C (min.) (Asheville Station-SERCC).

Precipitation exceeds 150 cm yearly and increases with elevation (Shanks 1954). Annual snowfall totals 40-50 cm (Asheville Station, SERCC). The bedrock at Craggy Gardens is mica gneiss and schist consisting and soils are rocky, and shallow. The bedrock at Big Bald is granite-gneiss with soils consisting of stony loams that contain high organic matter and moisture year round (Perkins and Gettys 1939).

Craggy Gardens is a southern Appalachian grass/heath bald, while Big Bald is dominated by grasses. The vegetation is comparable consisting of various grasses and shrub species, while the forests bordering are characteristic of a northern hardwood forest type. *Q. rubra L.* is the dominant species on the south, west, and east aspects, which also includes the majority of the grass and heath at both sites. The southern Appalachians including these sites have historically experienced widespread human alteration including logging, grazing, and fire. These land-uses have altered forest structure and removed most of the oldest trees eliminating the potential for long-term climate reconstructions from tree rings.

Data Collection

The original intent of developing a *Q. rubra L.* chronology from Craggy Gardens was to reconstruct tree establishment into the grass/heath bald (Crawford 2007). However, after developing the chronology, it was apparent that inter-annual and decadal climate variability had been recorded by the open-grown *Q. rubra L.* establishing in the bald. The sampling design involved employing belt transects from the forest-grass boundary downslope (perpendicular to the contour) to mature forest. We classified mature forest based on four criteria 1) a mature well developed overstory; 2) persistence of coarse woody debris; 3) absence of grass in the understory; and 4) well developed contiguous leaf litter. *Q. rubra L.* falling within the belt transects were cored once using an increment borer at approximately 25 cm stump height.

Additional cores were collected from old trees growing in stressed conditions (e.g. rock outcrop), and dominant trees with crowns reaching or exceeding the canopy. Several mature *Q. rubra L.* were rotten in the center which prevented cores from reaching the pith. A total of 128 trees were sampled in and around the bald across six transects on the west and southwest facing slopes.

The sampling design at Big Bald involved selecting mature open-grown and interior mature *Q. rubra L.* Each tree was sampled twice at a stump height of 25–30 cm (Fritts 1976). We were not able to reach the centers of many of the largest *Q. rubra* L. because our borers were too short. A total of 45 trees were sampled within the bald and in mature forest on the west, south, and east facing slopes.

Chronology Development

Individual cores of each chronology were air-dried, mounted, and sanded with progressively finer grit sandpaper following standard dendrochronological techniques (Phillips 1985; Stokes and Smiley 1996). We cross-dated cores within each site to assign a calendar year to each ring using the techniques of signature years (Yamaguchi 1991) and skeleton plotting (in the case of trees older than 150 years)(Stokes and Smiley 1996). Yearly ring-widths of each core were measured to the nearest 0.001 mm using a Velmex Stereoscope. We used the cross-dating verification program COFECHA to insure all rings were assigned the correct calendar year (Holmes 1983).

In order to obtain the maximum signal to noise ratio in a tree-ring chronology from the eastern temperate forest, it is recommended to sample between 30 and 40 trees with two cores per tree (Fritts 1976; Fritts and Swetnam 1989). At Craggy Gardens, we used only the oldest and well-dated trees in the site chronology resulting in a total of 87 trees with 103 individual series. The Big Bald chronology contained 45 trees totaling 80 individual series. Both open-grown woodlands have been relatively free of ecological competition on annual ring-width formation; therefore, deterministic growth-trend estimation was selected for standardization. Deterministic models predict ring-width indices based on time (*t*) and are most suitable for undisturbed open canopy stands, especially with young trees demonstrating robust juvenile age trends (Fritts 1976; Cook and Kairiukstis 1990). Individual series were interactively detrended using ARSTAN to obtain standard and residual chronologies of *Q. rubra L.* for both sites (Cook 1985).

Either a negative exponential curve or "hugershoff growth curve" (i.e. modified general exponential curve) (Cook 1985; Cook and Kairiukstis 1990) was fitted to each series to obtain dimensionless ring width indices by dividing the measured ring-width by the expected ring-width. This procedure retains the high frequency variability (inter-annual and decadal) and filters the medium and low frequency variability. For each series, temporal autocorrelation was removed with autoregressive modeling and each series was averaged using the biweight robust mean to reduce the influence of statistical outliers in computation of the mean chronology for each year (Cook 1985). A negative exponential curve corrects for an increase in radial growth during the juvenile phase followed by a subsequent decrease in ring-width as the tree reaches maturity. A general exponential curve corrects for pith offset, missing inner-rings, and strong juvenile age related growth trends followed by a decline in radial growth as the tree matures (Cook 1985; Cook and Kairiukstis 1990). These growth models appeared to be the best fit considering the open-grown conditions and unknown piths dates associated with several large diameter *Q. rubra L.* at each site. The general exponential curve or "hugershoff growth curve" has not been typically used in dendrochronology, although it is commonly used by foresters in growth increment estimation. However, these curves are considered theoretically complete compared to models that only fit declining radial growth with tree maturation (Cook and

Kairiukstis 1990). More recently, general exponential growth curves have been used to standardize chronologies when investigating tree sensitivity to temperature and differing strengths of climate signals associated with tree age (Briffa et al. 1998a; Wilson et al. 2004).

Climate-Tree Growth Response

In order to numerically express the relationship of tree growth to climate, we computed correlations functions and response functions using annual ring-width and monthly mean temperature, total monthly precipitation, and monthly Palmer's Drought Severity Index (PDSI) (Fritts 1976; Biondi and Waikul 2004). Statistical significance of $p < 0.05$ is typical for most dendroclimatic studies (Fritts 1976). Some researchers suggest that simple correlation may not be adequate when identifying significant relationships; therefore, bootstrap confidence intervals for correlation and response functions are needed to reduce the possibility of interpreting false significance and to strengthen estimates for climate-tree growth calibration (Fritts and Swetnam 1989; Guiot 1991; Biondi and Waikul 2004).

Another important consideration when quantifying climate- ring-width relationships is autocorrelation. Oftentimes biological tree growth exhibits interdependence on a given climatic variable and is correlated with ring-widths of the previous or current year being $t - 1$ or $t + 1$ (Fritts 1976). We removed temporal autocorrelation using autoregressive modeling where residual chronologies were computed (Cook 1985; Cook and Kairiukstis 1990). For this study, mean monthly temperature, total monthly precipitation, and monthly PDSI datasets from (1895-2005) were extracted from the National Climate Data Center for North Carolina Climate Divisions 1 (southern mountains) and 2 (northern mountains). Craggy Gardens and Big Bald are high elevation sites, distant from meteorological stations. Data for a single station would not have provided adequate representation of the climate conditions. Instead we used regionally averaged data from multiple stations (Blasing et al. 1981). Using the program DENDROCLIM2002 (Biondi and Waikul 2004), bootstrap correlation and response functions were derived from the previous March to current November (i.e. a 21-month period where the previous March is the beginning of the growing season of the prior year and the current November is the end of the current growing season) for both *Q. rubra L.* residual ring-width chronologies over a single period from 1896 to 2005 to identify significant climatic variables (Biondi and Waikul 2004).

Signal Stability and Strength

We evaluated the stability and strength of each climate signal identified by the correlation and response functions; however, each signal had to have commonality for each chronology to test the stability. For this analysis, May-June mean monthly temperature from the previous year and July mean monthly temperature for the current year over the period 1896–2005 were identified as the climate significant signals. This procedure involved using a two-stage regression procedure including 1) a moving window regression (Wilson and Elling 2004; Wilson et al. 2004), and to further validate the data 2) a split-period calibration using multiple stepwise regression and a series of verification statistics (Fritts 1976; Cook and Kairiukstis 1990; Fritts 1991).

The moving window regression tested for the stability of the temperature signals over the period 1896 to 2005 where ring-width at time (*t*) was the predictand and the climatic variable was the predictor in time (*t*) and (*t* -1). The moving regression employed a 15-year window shifting forward five years after each calculation. A 15-year moving window is expected to increase the possibility of identification of sensitive outliers and subtle changes in signal stability (Wilson et al. 2004)**.** Once the temperature signals were assessed, we split the single period 1896–2005 into three separate calibration periods: 1896–1939, 1926–1969, and 1970–2005.

These periods were selected based on the apparent stability of the temperature signals obtained from the moving window regression. Several studies suggests that numerical calibration of tree-ring widths and instrumental climate data using least squares regression over the past two decades, in which an equality of the means is assumed, may in fact overestimate or underestimate past and present climate variables and tree ring-width estimates due to observed warming trends (Briffa et al. 1998a; Briffa et al. 2004).

We selected the significant temperature variables for use in multiple stepwise regressions. Annual ring-widths from the residual chronologies were calibrated using previous (t - 1) May-June mean monthly temperature from Division 1 and previous May mean monthly temperature from Division 2 as candidate predictors. Separate calibrations were developed for each of the over-lapping periods (model 1, 1896–1939) and (model II, 1926–1969). For the period 1970–2005, residual chronologies were calibrated with current (t) July mean monthly temperature for climate divisions 1 and 2 as candidate predictors. Other calibrations were developed spanning the same calibration intervals but were not statistically significant ($p < 0.05$) validating the results derived from the moving window regression.

Finally, we verified each calibrated regression model by withholding independent instrumental data from the calibration period during 1896–1925, 1940–1969, and 1970–2005 for the previous May-June models and 1896–1969 for the current July model. The independently withheld instrumental data was then entered into the appropriate calibrated model equation to obtain estimates of ring-widths in time (t) in the verification period. We then compared the estimated ring-widths with the actual ring-widths using a series of verification statistics product moment correlation (r), reduction of error (RE), coefficient of efficiency (CE) and sign test (Fritts 1976; Cook and Kairiukstis 1990; Fritts 1991; Cook et al. 1999).

Results

Chronology Comparisons

The descriptive statistics for each *Querus rubra* L. chronology revealed similarities between statistical properties, despite considerable differences in the number of trees used for each chronology development (Fig. 2, Table 1). Craggy Gardens constitutes the longest time series, however, the majority of the trees were 80 years and younger. The Big Bald chronology, on the other hand was shorter in length, but was composed mainly of trees 100 years and older. Interestingly, the difference in sample size did not appear to cause substantial variation in chronology statistics (Table 1). Identical signature year ring-width patterns and high frequency variability were observed in both chronologies indicating a common climatic response in *Q. rubra* L. (Fig. 2). A rotated varimax principal components analysis (PCA) (Tardif and Conciatori 2006b; Tardif et al. 2006) of both chronologies showed that PC1 accounted for 57.2% common variance and PC2 revealed 42.8% common variance. Pearson's correlation analysis corroborated the PCA, indicating that both chronologies had significant variation $r = 0.49$ ($p < 0.001$) (Fig. 2). The mean sensitivity for each chronology was similar, but was slightly higher in the Craggy Gardens chronology (Table 1).

A high degree of autocorrelation between year to year ring-widths revealed that the previous year's growth influenced subsequent growth formation in *Q. rubra* L. (Table 1). The inter-series correlation within each chronology indicated a strong common signal between trees at both sites (Table 1). When all 132 trees and 183 series were compared, the inter-series correlation was r = 0.56, indicating that in addition to a common tree to tree signal there was also a strong macro signal covering 35 km or greater (e.g. distance between Craggy Gardens and Big Bald). The expressed population signal reflects chronology quality where the actual chronology is compared with a theoretical population chronology calculated from an infinite number of trees. The expressed population signals for both chronologies between 1895 and 2005 were above the suggested threshold of 0.85 (Cook 1985; Cook and Kairiukstis 1990) with one exception in the Craggy Gardens chronology, in which the 25 year interval of 1895–1920 was 0.70 (Table 1).

Climate Tree-Growth Response

The *Querus rubra* L. ring-width-climate correlation and response functions were slightly different between site chronologies. Both chronologies showed a similar response to both instrumental datasets Divisions 1 and 2 (Fig. 3). The relationship between ring-width and mean monthly temperature was consistently positive in both the previous year and current year's growing season (Fig. 3). Previous May-June and current July temperatures were statistically significant (positive) for both ring-width chronologies. Current April temperature showed a positive relationship with growth at Craggy Gardens, while current November temperature was positive in Big Bald (Fig. 3).

The relationship between ring-width and total monthly precipitation was indistinct with current October precipitation standing as the only positive significant variable for Craggy Gardens; however, there was a negative response to previous June precipitation (Fig. 3). There was no relationship or consistent response between the Big Bald chronology and total monthly precipitation (Fig. 3). The relationship between ring-width and monthly PDSI was noticeable in the year previous to ring formation, which corroborated the response (negative) to previous year's June precipitation. Previous June PDSI was statistically significant (negative) in both chronologies (Fig. 3). The response of the Big Bald chronology differed from Craggy Gardens in that previous March, May-August PDSI were also statistically significant (negative) (Fig. 3). Both previous and current year's growing season temperatures appear to have the strongest influence growth of *Q. rubra L.* at both sites, along with previous year's drought conditions, especially in the early growing season where water availability is crucial for radial growth.

Signal Stability and Strength

Two moving window regressions were developed to evaluate the temperature signals of previous May-June and current July mean monthly temperature for each site chronologies over the period 1896–2005. The May-June moving window for Craggy Gardens showed that early growing season temperature from the previous year explained 11%–49% of the variance between 1896 and 1970. From 1970 to 2005 the explained variance declined from 5%–31%. The decades 1910–1930 and 1950–1970 were distinct explaining 27%–49% and 33%–42% of the variance, respectively. The July moving window for Craggy Gardens revealed that after 1970 current growing season temperature explained 12%–60% of the variance with the highest percentage being between 1980 and 1990. There was no temperature signal for July before 1970.

The May-June moving window for Big Bald was similar to that of Craggy Gardens showing that early growing season temperature from the previous year explained 19%–45% of the variance between 1896 and 1970. The variance decreased after 1970 ranging from 8%–30%. The periods 1910–1930 and 1950–1970 explained the most variance from 27%–43% and 27%–31%, respectively. The July moving window for Big Bald showed that current growing season temperature after 1970 explained 11%–52% of the variance with a distinct period of higher variance during 1980–1990. As at Craggy Gardens, there was no July temperature signal before 1970.

Three multiple stepwise regression models for each chronology were developed to further test the stability and strength of temperature signals identified in *Querus rubra* L. by calibrating annual ring-widths with monthly temperature, and then predicting annual ring-width from independently withheld temperature variables. To avoid the possibility of spurious regressions, monthly temperature variables including previous May-June, and current July were screened at a $p < 0.05$ before entering the stepwise regression model. Both May-June calibrated models were consistent in their variance for Craggy Gardens indicating a coherent signal from 1896–1969 (Fig. 4, Tables 2 and 3); however, the calibrated May-June model I for Big Bald explained more variance than the May-June model II indicating a slight change in signal stability between 1896–1969 (Fig. 4, Tables 2 and 3). For the July models, Craggy Gardens had a higher variance than Big Bald, but both models performed well suggesting a clear temperature signal after 1970 at a regional scale (Fig. 4, Tables 2 and 3). The difference in predictive variance between Craggy Gardens and Big Bald suggest that younger *Q. rubra L.* trees may be more sensitive to temperature changes, especially when positive association enhances growth.

To test the predictive skill of each model, a series of verification statistics were applied to periods where independent temperature variables had been withheld, and then used to predict annual ring-width (Fritts 1976; Cook and Kairiukstis 1990; Fritts 1991). For Craggy Gardens, neither May-June models passed the verification tests for the periods 1896–1925 and 1940–1969 indicating that the temperature signals may have varied from year to year or even across decades (Fig. 4, Table 2 and 3). An important factor that may have contributed to model I failure was the lack of a sufficient EPS value (1895–1920) associated with sample depth for the chronology (Table 1). Conversely, both May-June models did verify for the 1970–2005 period with the exception of the sign test (Fig. 4, Tables 2 and 3) suggesting that *Querus rubra* L. growing at Craggy Gardens had consistent sensitivity to temperature after 1970, but the decadal drought in the 1970s had significant effect on model predictability in event years. For Big Bald, the May-June model I failed the verification tests during 1940–1969, but model II performed well for the

1896–1925 period (Fig. 4, Tables 2 and 3). During the 1970–2005 verification periods, model I passed the reduction of error statistic indicating some predictive power, but not unanimously; however, model II passed verification tests in the 1970–2005 period with the exception of the sign test (Fig. 4, Tables 2 and 3). Big Bald had a large fraction of older trees compared to Craggy Gardens; therefore, differing performances of the models points to a possible age related climate response. On the contrary, shifts in sensitivity to temperature after the early part of the twentieth century appears to have no dependency on *Q. rubra* L. age. Both site chronologies had similar responses to July temperature after 1970 further supporting this idea. Both chronologies failed the July model verification tests for the period 1896–1969 (Fig. 4, Tables 2 and 3).

Discussion

Chronology Comparisons

The strong association between the chronologies at both sites demonstrates that *Q. rubra L.* growing at their elevational distribution limit in the southern Appalachians respond to similar climatic variables. The number and relative frequency of narrow ring years coupled with strong autocorrelation in each chronology, suggests that extreme climatic conditions in the previous and current year are limiting to growth of high elevation *Q. rubra* L. This finding is further supported by the shared common variance and similarity between chronology statistics (Table 1). Several other studies of *Quercus spp*. and other trees growing at or near the latitudinal boundaries showed high common variance and response to extreme climatic events indicating a regional tree-growth climate response (Gramulich 1993; Tardif et al. 2001; Pederson et al. 2004; Tardif and Conciatori 2006a; Tardif and Conciatori 2006b).

Within the southern Appalachian region, our identification of narrow ring years are consistent with other studies of both *Q. rubra L.* and *Q. alba L.* at differing elevations (Tainter et al. 1984; Jacobi and Tainter 1988; Tainter et al. 1990) where periodic droughts (e.g., 1911, 1925, 1936) and episodic droughts (e.g., 1950s and 1970s) were responsible for reduced radial growth. Identical ring-width patterns and equivalent inter-series correlations in both *Q. rubra L.* chronologies indicate that drought conditions (e.g. inter-annual and decadal) are limiting to growth independent of tree age. Our study supports the idea that there is a strong common climate forcing of *Querus rubra* L. radial growth at lower latitude high elevations. Together with the higher latitude studies (Gramulich 1993; Tardif et al. 2001; Pederson et al. 2004; Tardif and Conciatori 2006a, 2006b; Tardif et al. 2006), our research suggests that climate conditions are important in controlling radial tree-growth in northern hardwood deciduous forest ecotones and that clear signals can be extracted from *Quercus spp*. in high elevation locations of the southern Appalachians.

Climate-Tree Growth Response

The response of both *Q. rubra L.* site chronologies was strongly correlated with mean monthly temperature, which is a common signal with trees growing at their elevational limits (Fritts 1976). Because temperate high elevations receive in excess of 150 cm of precipitation annually (Shanks 1954), weak relationships between total monthly precipitation and radial growth indicates that precipitation is not limiting; however, significant negative responses to monthly PDSI shows that years with limited precipitation in the early growing season, higher temperatures, and below average soil moisture caused a reduction in radial growth due to water stress. *Querus rubra* L. tends to grow on mesic sites, south, and west aspects. Biological adaptations such as deep roots, water transport, and xeromorphic leaves allow for drought tolerance in *Q. rubra* L. Even so, it is more sensitive compared with *Q. alba L.* which is characteristic of drier sites (Abrams 1990). Given this relationship, distinct and consistent temperature response signals of *Q. rubra* L. growing at high elevations can be clearly identified when precipitation is adequate for radial growth; however, if drought conditions are persistent, then temperature response signals may become less pronounced with extreme climatic conditions such as drought stress becoming the dominant signal.

Both early growing season temperature in the year previous to ring formation, and summer growing season temperature in the year of ring formation were significantly correlated with *Q. rubra* L. radial growth; in addition, to previous year's PDSI. Our results are consistent with several earlier studies. Tardif et al. (2006), Tardif and Conciatori (2006a) in their analysis of *Q. rubra* L. and *Q. alba* L. at the northern limit of *Q. alba* L. found that spring temperature and summer precipitation were important for growth, with *Q. rubra* L. being particularly sensitive to the previous year's summer water balance. Tardif and Conciatori (2006b) in a similar study concluded that different climatic variables controlled earlywood and latewood growth in *Q. rubra* L. and *Q. alba* L. Garcia-Gonzalez and Eckstein (2003) showed that earlywood vessel development in *Quercus robur* L. on a maritime site was dependent on moist and cool conditions in the late winter of previous year and early spring of the current year. Zasada and Zahner (1969) in their analysis of *Q. rubra* L. earlywood formation found that radial expansion lasted for 10 weeks in the early growing season.

In the southern Appalachians and surrounding region, our results contrast with those of several studies where Tainter et al. (1984) found that *Q. rubra* L. earlywood had a positive response with previous winter temperatures, and negative response to spring precipitation. Latewood was positively associated with previous summer temperature and negatively with current summer temperature. Jacobi and Tainter (1988) found that *Q. alba L.* had a negative response to summer temperature, positive response to late fall temperatures for the previous year, and positive response to spring precipitation in current year. Tainter et al. (1990) showed no consistency in the response of *Q. rubra L.* to temperature or precipitation across four sites. Our results were more similar to Pan et al. (1997) who found that *Q. rubra* L. responded positively to previous year's growing season temperatures. Our results corroborate those of Terrell and Leblanc (2002) who found that *Q. rubra L.* responded significantly to the previous year's early season growing conditions across 71 sites in eastern United States. In addition, LeBlanc and Terrell (2001) in their analysis of 128 sites and Rubino and McCarthy (2000) showed the current growing precipitation was important for *Q. alba L.* radial growth.

Although our results are not completely consistent with individual studies of *Q. rubra* in the southern Appalachian region, they matched much more closely with the climatic response of *Q. rubra L.* and *Q. alba* L. at its northern and western distribution limits. Early growing season (May–July) temperature and precipitation appear to be the principal seasonal variables for *Q. rubra L.* and *Q. alba L.* radial growth, especially, in the previous year for *Q. rubra L.* Numerous authors have suggested that warm early growing temperatures would have a significant positive effect on radial growth (Jacobi and Tainter 1988; Gramulich 1993; Pan et al. 1997; Bassow and Bazzaz 1998). Several studies have also concluded that early growing season water availability is critical for radial growth in *Q. rubra L.* and *Q. alba L.* (Abrams 1990; Foster and LeBlanc 1993; Rubino and McCarthy 2000; LeBlanc and Terrell 2001; Terrell and LeBlanc 2002; Garica-Gonzalez and Eckstein 2003; Tardif and Conciatori 2006b; Tardif et al. 2006). Yet, factors contributing to inconsistencies between our results and others may be associated with the differing climatic response of *Q. rubra L.* at high elevations versus lower elevation sites. Also, different standardization methods and instrumental datasets used for numerical calibration of radial growth and climate associations could be other reasons.

Signal Stability and Strength

Based on bootstrap correlation and response functions, two distinct temperature signals were identified in *Q. rubra* L. over the common interval of 1896–2005 from both sites. In our moving window regression analysis, results indicate a similar stable early growing season response to temperature at both sites from 1896–1969; however, an apparent slight reduction in sensitivity was observed after 1970. Throughout the common interval of analysis, a reduction in signal strength of May-June temperature appeared to be in both chronologies, especially in the decades 1940–1950 and 1970–1990. For the July moving window model, there was no temperature signal before 1970, but after 1970, a stable signal was found explaining 41%–60% of the variance between 1980 and 1990 across both chronologies.

The periods of reduced signal strength appears to correspond closely with both documented regional droughts in the late 1940s and early 1950s and throughout the 1970s (Tainter et al. 1984; Jacobi and Tainter 1988; Tainter et al. 1990). Additionally, the reduced May-June signal also aligns with the emergence of a prominent July temperature signal between 1980 and 1990. High signal detection reflects a common climate forcing among trees, where as, low signal strength indicates other environmental factors are affecting growth. Deviations in signal stability also suggest varying year to year responses mainly resulting from outliers (i.e., narrow ring-widths indicate extreme events), but may only be present in one or two years intervals which can significantly weaken the time-stable climate signal (Wilson and Elling 2004). Both of these simultaneous climatic episodes indicate that *i*) annual, inter-annual, and decadal drought stress is a threshold by which time-stable temperature signals can be identified in *Q. rubra L.* and *ii*) the apparent shift or additional temperature response from the previous early growing season to current summer temperature had significant effect on signal stability after 1970, especially between 1980 and 1990.

Given the similar climatic responses of both chronologies, differences in sample size and age structure of both chronologies appeared to have little effect on the results. Although our analysis did not directly focus on age dependent climate-growth response, other studies do support such findings. Wilson et al. (2004) found that trees greater than 110 years of age and less than 100 years were strongly correlated with precipitation and demonstrated a common signal independent of age. Carrer and Urbinati (2004) showed that *Larix decidua* and *Pinus cembra* responded to climate based on tree age and the same climatic variables were limiting to growth, but younger trees (<100) years had weaker responses. They suggested that younger trees could better cope with adverse climatic conditions. Our findings are in agreement with that study in that *Q. rubra L.* older than 100 years in age and younger than 100 years were limited by the same climatic variable (early growing season precipitation); however, we found younger trees reflected an increased sensitivity to positive temperature changes, in particular at Craggy Gardens.

Our results are comparable with several studies that have showed a reduced sensitivity to temperature and temporal-instability in climate-tree-growth associations over the past four decades. Briffa et al. (1998a, 1998b) in their analysis of tree ring chronologies at the northern high latitudes found an increasing divergence between spring and summer temperature and tree growth after 1960 across the northern hemisphere. They suggested ozone depletion**,** increased competition, and tree growth-soil moisture balance as possible casual factors. Biondi (2000) found an apparent shift in *Pseudotsuga menziesii* (Mirb.) response from June precipitation to May precipitation and also a negative response to April temperatures in recent decades in a study in central Idaho. In addition, Biondi (2000) identified May and June PDSI as significant predictors after 1970 indicating increased drought stress. Solberg et al. (2002) found that *Picea abies* growing in a coastal climate experienced a reduced sensitivity to spring temperature over the 20th century with an increasing sensitivity to summer climate conditions. Wilson and Elling (2004) revealed that *Abies alba* (Mill) demonstrated an unstable climate response in recent decades mostly attributed to regional SO² emissions. Buntegen et al. (2006) showed that high elevation *Picea abies* L. (Karst) demonstrated increased sensitivity to drought stress with a shift from summer growing season temperature to mixed signals of previous year's precipitation and temperature. Carrer and Urbinanti (2006) in further examination of *Larix decidua* found changes in temperature response indicating the trees greater than 200 years in age became more sensitive to 19th and 20th century temperature with an extended growing season facilitated by July precipitation and temperature.

In relation to our study of *Q. rubra L.*, positive response to early growing season temperature suggests that warmer temperatures enhance radial growth resulting in an extended growing season. This reflects an increased sensitivity to temperature at our sites rather than reduced sensitivity as found by several studies at high latitudes (Briffa et al. 1998a, 1998b; Solberg et al. 2002). Moreover, the apparent reduced sensitivity of tree growth to spring and summer temperatures at high latitudes could be the same climatic mechanisms causing an increased sensitivity of tree growth at lower latitude high elevations as indicated by our study. Our study also not only reflects a positive response to early growing season temperatures, but reveals a distinct shift from a dominant spring temperature response from the previous year to an additional response to summer temperature in the current growing season after 1970. This is consistent with other studies that have showed tree-growth climate responses shifting over recent decades most notably during the spring and summer growing seasons (Biondi 2000; Wilson and Elling 2004; Buntegen et al. 2006; Carrer and Urbinanti 2006).

As a means of further testing the time-stable temperature responses in *Q. rubra L.*, three multiple stepwise regression models were developed for the purpose of predicting annual ring-width from independently withheld temperature data (Fig. 4, Table 2 and 3). Numerical calibrations for each site chronology were obtained for the early and middle periods of the 20th century. Calibrating in recent decades in known to impose bias with least squares where the tendency would be to over- and under-estimate past and present temperature (Briffa et al. 1998a; Briffa et al. 2004). The calibrated variance for the May–June temperature models was low but stable; however, the July models explained higher variance after 1970 validating the moving window regression. Increasing the calibration interval, reduces in the amount of explained variance suggesting that including more drought years lessen temperature model predictability for *Q. rubra L.* ring-width. Visual comparison of actual and predicted annual ring-widths in each verification period revealed that each temperature model consistently failed to predict narrow ring drought years (Fig. 4).

Each May-June temperature model for the most part passed verification tests between 1970 and 2005 except for the sign test (Table 2 and 3). Sign test is a non-parametric verification statistic that highlights whether tree growth and climate estimates change and departure in similar directions, and if they depart in opposite directions of the sample mean, they are considered to disagree. We identified that drought events affect temperature response signals in *Q. rubra* L. The failure of the sign test to pass verification highlights that the decadal drought of the 1970s hampered the ability to predict stable temperature-ring-width estimates in terms of annual departures from the sample mean. This supports the idea that drought conditions significantly affect temperature-ring-width relationships and that the sign test proved useful in identifying the affects of extreme climatic events of annual ring-width of *Q. rubra* L. Even though there was a reduction in May-June temperature response after 1970, early spring temperatures and water availability are still important for *Q. rubra L.* growth in the year previous to ring formation. Failure of the July temperature models to predict annual ring-width before 1970 confirms the moving window regression (Fig. 4, Table 2 and 3) and Briffa et al. (1998a), Briffa et al. (2004) conclude that calibrating in recent decades using least squares regression will yield bias estimates. The secondary validation of signal stability and strength in *Q. rubra* L. using split period calibration and verification statistics supports the conclusions of several authors, who are in agreement that there has been a shift in climate-tree growth response over past four decades (Briffa et al. 1998a, 1998b; Biondi 2000; Solberg 2002; Briffa et al. 2004; Carrer and Urbinati 2004; Wilson and Elling 2004; Wilson et al. 2004; Buntegn et al. 2006; Carrer and Urbinati 2006).

Conclusions

Our dendroclimatic analysis has identified that *Q. rubra* L. growing at its elevational limit in the southern Appalachians exhibits positive responses to early growing season temperature and negative responses to drought. These results also indicate that *Q. rubra L.* growing in the southern Appalachians at high elevations regionally cross-date reflecting a common climatic forcing upon growth. Although few long-term records exist for this region and forest type, the development of a two to three century time series may be possible with appropriate site selection. The shared common variance among two differing sites highlights the prospect for expansion of a regional network to extend the *Q. rubra L.* time series, and for required replication of results.

In addition to network expansion, comes the need to understand the effects of past and present climatic variability on *Q. rubra L.* growth and what future responses may be under a continued warming scenario. Several authors have suggested that time-stability of climate-tree growth associations need to be evaluated across many different regions and species to insure that calibrations are accurate when used for reconstructions. This demand comes for several studies that indicate that climate signals have shifted over the past century and even more so in past four decades (Briffa et al. 1998a, 1998b; Biondi 2000; Solberg et al. 2002; Briffa et al. 2004; Carrer and Urbinati 2004; Wilson and Elling 2004; Wilson et al. 2004; Buntegn et al. 2006; Carrer and Urbinati 2006).

Though this analysis is based only on two *Q. rubra L.* chronologies, the correlation and response functions on 132 total trees indicate a common positive temperature response across the region. The use of a moving window regression coupled with dendroclimatic calibration and verification statistics proved useful in understanding the effects of annual, inter-annual, and decadal drought on temperature signal stability in *Q. rubra L.*, and points towards a shift in temperature response of *Q. rubra L.* after 1970. This analysis contributes to both a larger body of literature on *Q. rubra L.* climate-growth associations (Tainter et al. 1990; Gramulich 1993; Pan et al. 1997; Terrell and LeBlanc 2002; Pederson et al. 2004; Tardif and Conciatori 2006, 2006; Tardif et al. 2006) and regional understanding of the biological and ecophysical responses of *Q. rubra L.* to climate variation at its ecological tolerance range in southern Appalachians.

However, caution must be used in interpreting the response of *Q. rubra L.* to northern hemispheric warming, as neither air pollution nor increased nitrogen deposition can be ruled out as contributing factors in the changing growth response of *Q. rubra L.* This analysis does highlight the need to further investigate southern high-elevation forests and their response to present and future climate changes.

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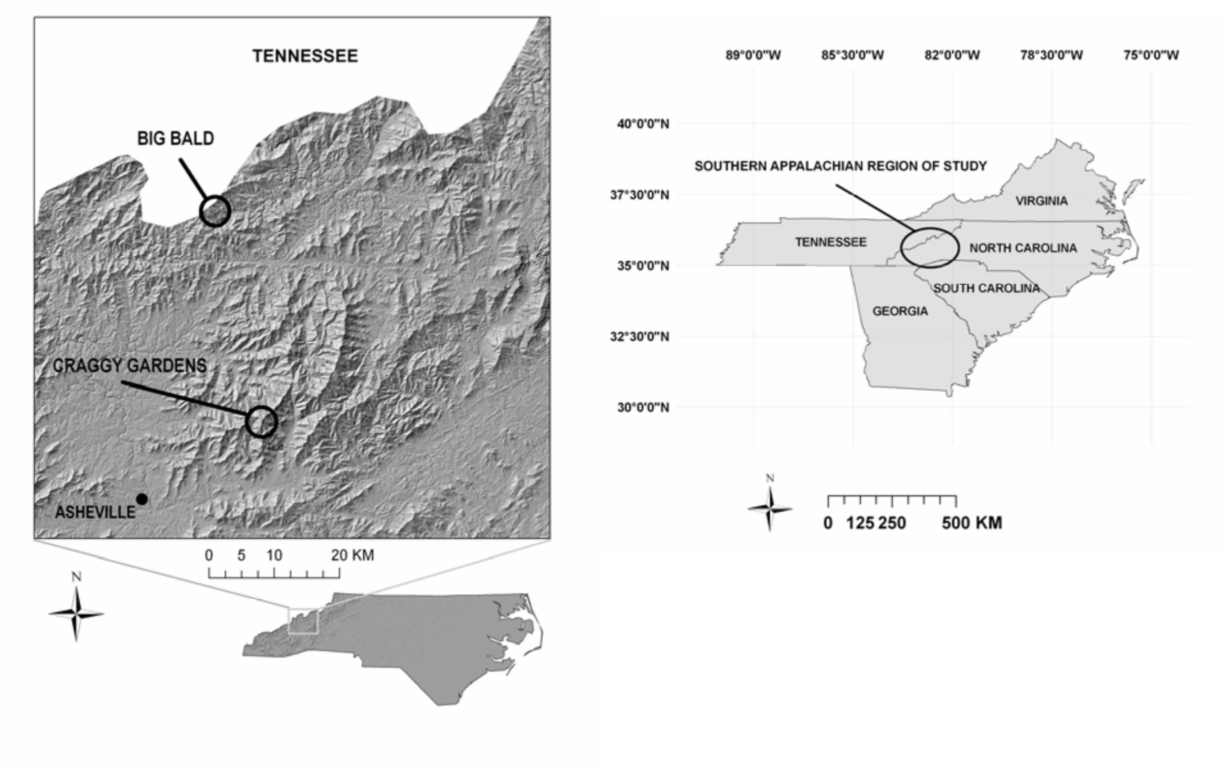


Figure 1. A map of the study region including the study sites in the southern Appalachians of western North Carolina. Craggy Gardens and Big Bald are approximately 35 km apart in two differing mountain ranges, Great Craggy Mountains and Bald Mountains, respectively.

Table 1. Descriptive residual ring-width chronology statistics for *Q. rubra L.*

Site:	Craggy Gardens	Big Bald
Chronology length	1763-2005	1816-2005
Number of trees	87	45
Number of radii	103	80
Mean sensitivity[a]	0.23	0.21
Inter-series Correlation[b]	0.61	0.60
First-order autocorrelation[c]	0.57	0.55
Expressed population signal[d]		
1895	0.70	0.97
1920	0.86	0.98
1945	0.98	0.98
1970	0.99	0.97

Note: Statistics were calculated by ARSTAN (Cook 1985) and COEFECHA (Holmes 1983) for both master site chronologies spanning the period 1763-2005 and 1816-2005, respectively.

[a] Mean sensitivity is the difference involving consecutive ring indice values signifying the occurrence of high-frequency variability (Fritts 1976).

[b] Mean correlation between all radii (Holmes 1983).

[c] Standard chronology calculation (Cook 1985).

[d] Expressed population signal denotes tree-ring chronology reliability. The statistic is a comparison between the actual chronology and a theoretical population chronology calculated from an infinite number of trees, where 0.0 indicates no agreement and 1.0 indicates perfect agreement. A chronology with value greater than 0.85 is considered dependable (Cook 1985; Cook and Kairiustis 1990).

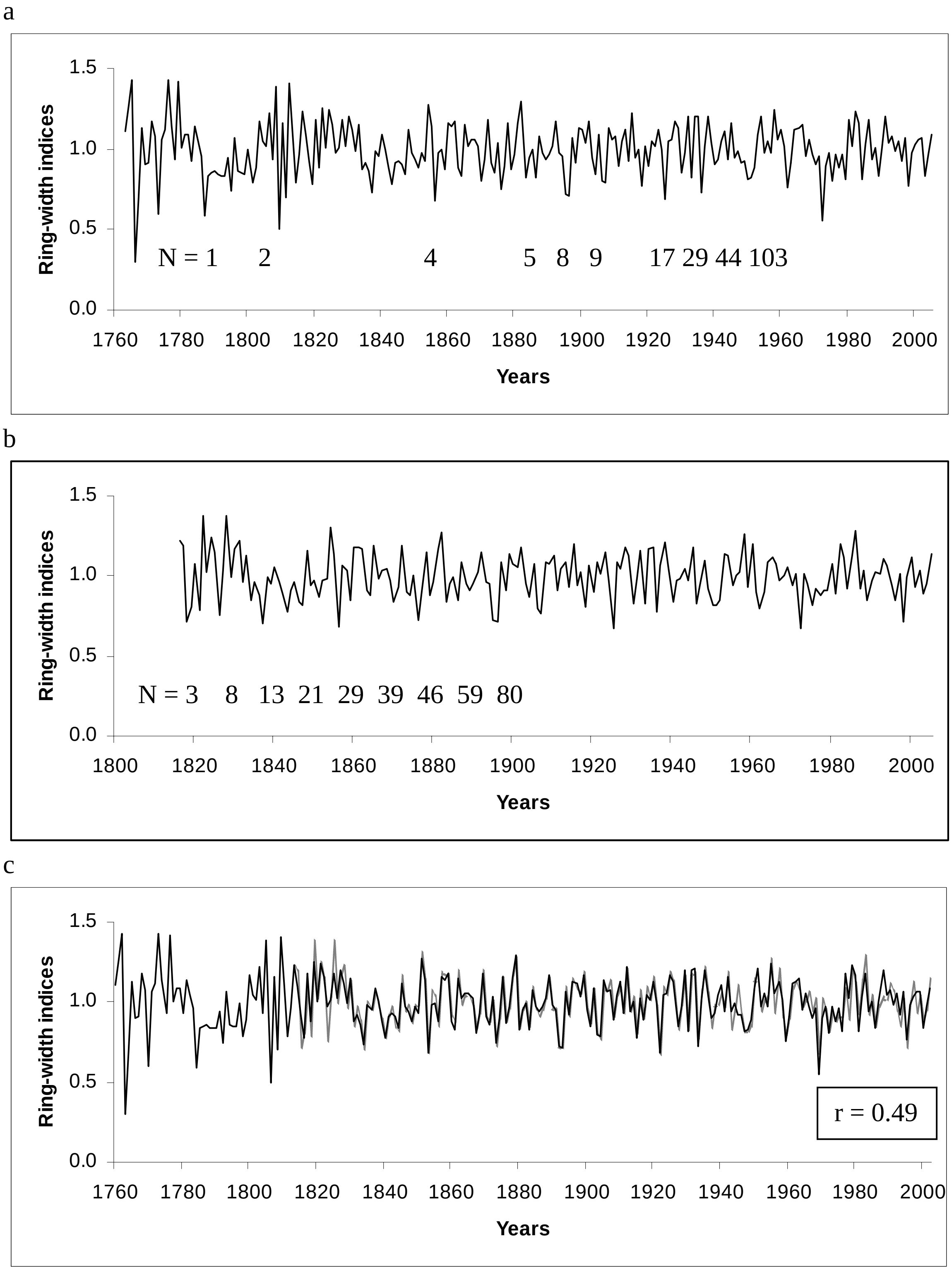


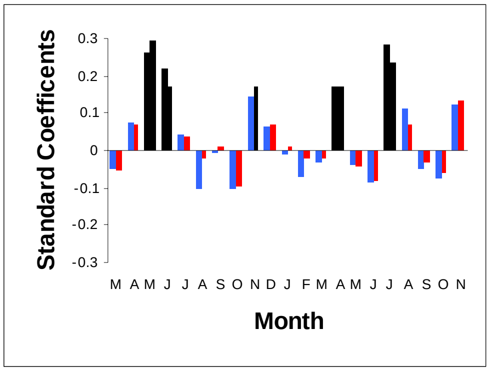
Figure 2. *Querus rubra* L. residual ring-width chronologies developed from Craggy Gardens and Big Bald. a) Craggy Gardens 1763-2005. b) Big Bald 1816-2005. c) A comparison of high frequency variability of both *Q. rubra L.* residual chronologies. The black line represents Craggy Gardens and the dotted line represents Big Bald. Pearson's correlation analysis yielded $r = 0.49$ covariance ($p < 0.001$). N represents the number series used to calculate residual ring-with chronologies.

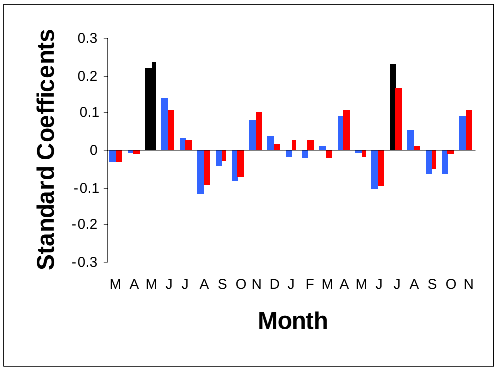
Craggy Gardens

Correlation Functions

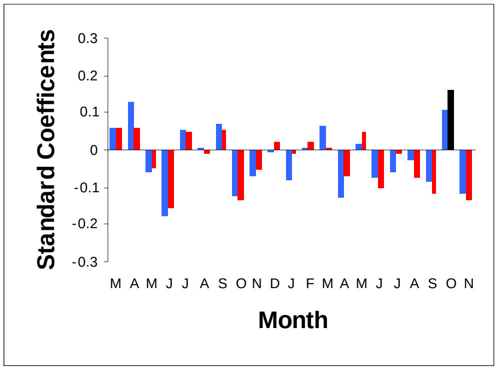
Response Functions

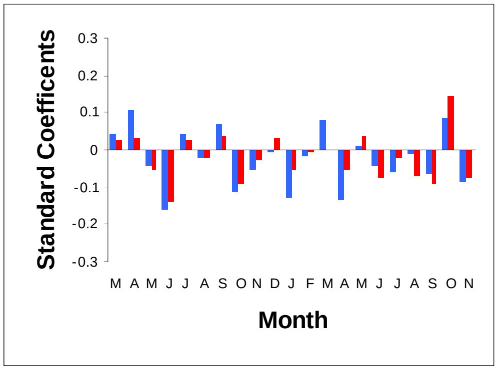
Mean Monthly Temperature



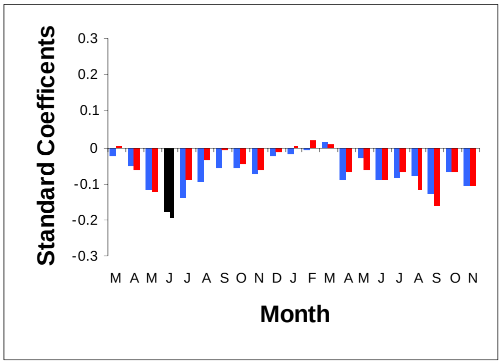


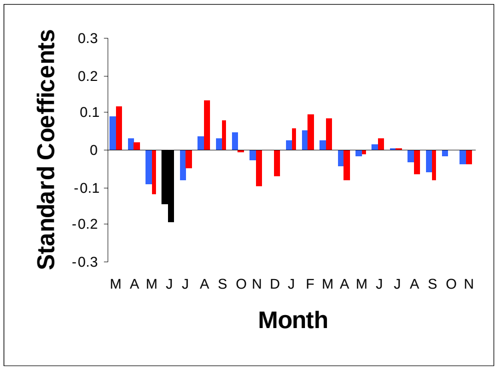
Total Monthly Precipitation





Monthly PDSI



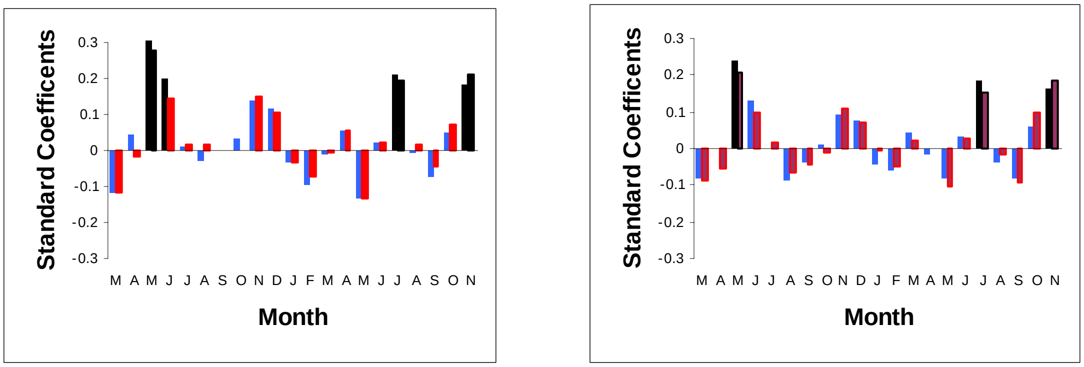


Big Bald

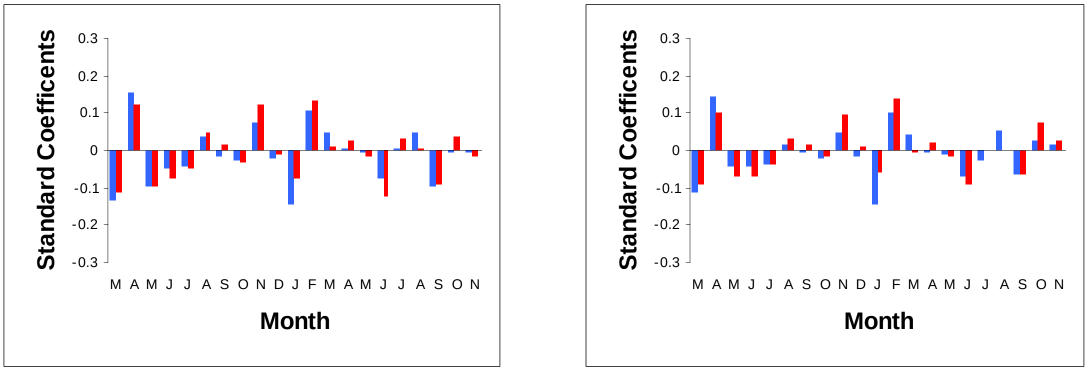
Correlation Functions

Response Functions

Mean Monthly Temperature



Mean Monthly Precipitation



Monthly PDSI

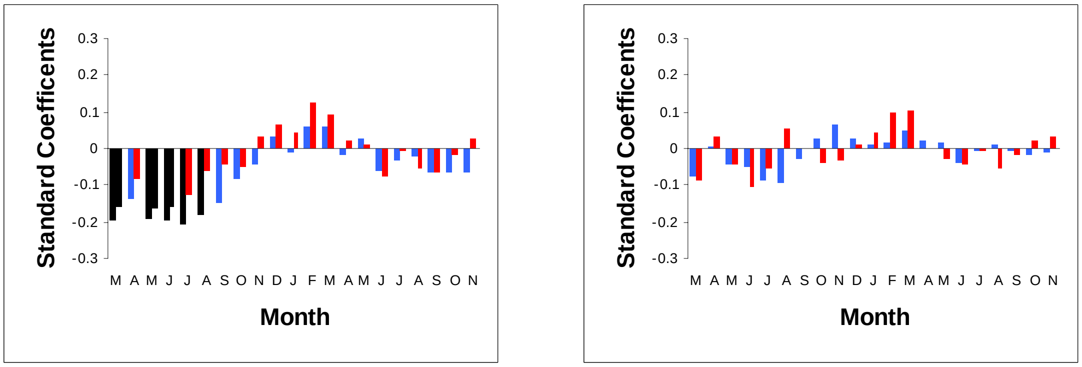


Figure 3. Represents the bootstrap correlation and response functions for each *Q. rubra L.* residual ring-width chronology. The blue bars indicate coefficients derived from residual ring-widths and North Carolina Climate Division 1 (southern mountains) datasets for the period 1895-2005. The red bars indicate coefficients derived from residual ring-widths and North Carolina Climate Division 2 (northern mountains) datasets for the period 1895-2005. The black bars indicate significant coefficients $p < 0.05$ as calculated by DENDROCLIM2002 (Biondi and Waikbul 2004).

Table 2. Craggy Gardens calibration and verification statistics for each stepwise multiple regression model developed to predict annual ring-width (RW) of *Q. rubra L.* from mean May-June, and July temperature (Fritts 1976; Cook and Kairiukstis 1990; Fritts 1991; Cook et al. 1999)

	May-June RW model I		May-June RW model II		July RW model
Calibration period	1896-1939		1926-1969		1970-2005
Verification period	1940-1969	1970-2005	1896-1925	1970-2005	1896-1969
Calibration					
Predictor Variables	May DV1, June DV1 (*t*-1)		May DV1, June DV1, and May DV2 (*t*-1)		July DV1, July DV2 (*t*)
r^2	0.17		0.22		0.33
Adjusted r^2	0.13		0.14		0.29
p	<0.05		<0.05		<0.05
Verification					
Pearson's correlation coefficient r	0.20	0.28	0.20	0.29	0.07
Reduction of error (RE)[a]	-0.12	0.08	-0.27	0.08	-0.39
Coefficient of Efficiency (CE)[b]	-0.13	0.07	-0.27	0.06	-0.39
Sign Test[c]					
Agreements	16	**23**	15	**20**	29
Disagreements	14	**13**	15	**16**	45
p	ns	<0.05	ns	<0.05	ns

Note: Mean monthly temperature variables (DV1 = North Carolina Climate Division 1 and DV2 = North Carolina Climate Division 2) were entered as predictors into each stepwise regression model only if $p<0.05$. Significance determined with one-tailed t-test. Bold numbers indicate verification statistics not passing $p<0.05$ significance.

[a] The Reduction of Error (RE) statistic is acceptable if greater than 0; a RE greater than zero indicates that the model estimate is superior to the calibration period mean.

[b] The Coefficient of Efficiency (CE) statistic is acceptable if greater than 0; a CE greater than zero indicates that the model estimate is superior to the verification period mean. The bold value indicates failure in the verification period.

[c] Results from a significant sign test show reliable trends in the annual variability of the actual and predicted data.

Table 3. Big Bald calibration and verification statistics for each stepwise multiple regression model developed to predict annual ring-width (RW) of *Q. rubra L.* from mean May-June, and July temperature (Fritts 1976; Cook and Kairiukstis 1990; Fritts 1991; Cook et al. 1999).

	May-June RW model I		May-June RW model II		July RW model
Calibration period	1896-1939		1926-1969		1970-2005
Verification period	1940-1969	1970-2005	1896-1925	1970-2005	1896-1969
Calibration					
Predictor Variables	May DV1, June DV1, and May DV2 (t-1)		June DV1, May DV2 (t-1)		July DV1 (t)
r^2	0.20		0.14		0.18
Adjusted r^2	0.14		0.10		0.15
p	<0.05		<0.05		<0.05
Verification					
Pearson's correlation coefficient r	0.24	0.22	0.30	0.30	0.13
Reduction of error (RE)	-0.10	0.02	0.06	0.08	-0.12
Coefficient of Efficiency (CE)	-0.12	-0.02	0.05	0.04	-0.12
Sign Test					
Agreements	15	21	21	**22**	33
Disagreements	15	15	9	**14**	41
p	ns	ns	<0.05	<0.05	ns

Note: Mean monthly temperature variables (DV1 = North Carolina Climate Division 1 and DV2 = North Carolina Climate Division 2) were entered as predictors into each stepwise regression model only if $p<0.05$. Significance determined with one-tailed t-test. Bold numbers indicate verification statistics not passing $p<0.05$ significance.

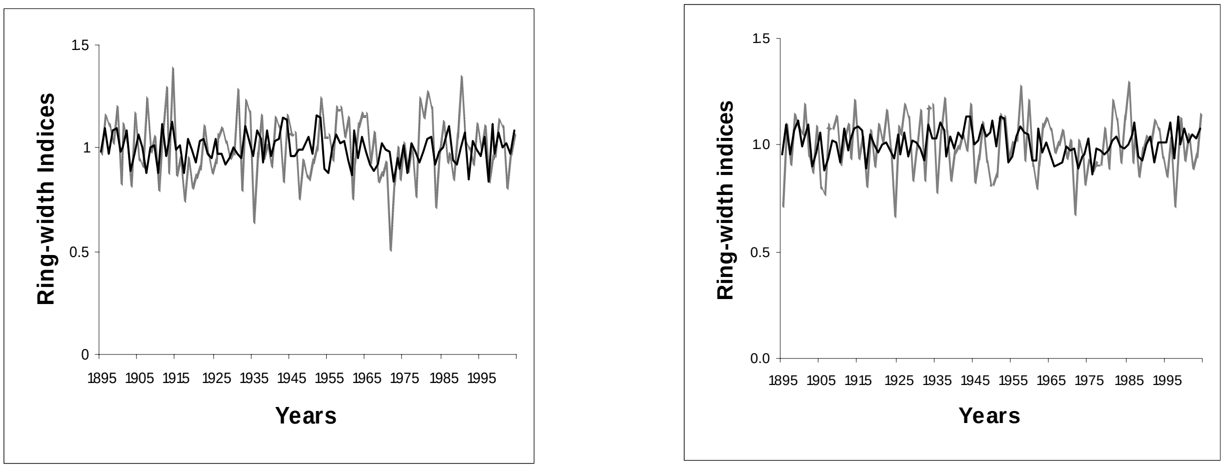
[a] The Reduction of Error (RE) statistic is acceptable if greater than 0; a RE greater than zero indicates that the model estimate is superior to the calibration period mean.

[b] The Coefficient of Efficiency (CE) statistic is acceptable if greater than 0; a CE greater than zero indicates that the model estimate is superior to the verification period mean. The bold value indicates failure in the verification period.

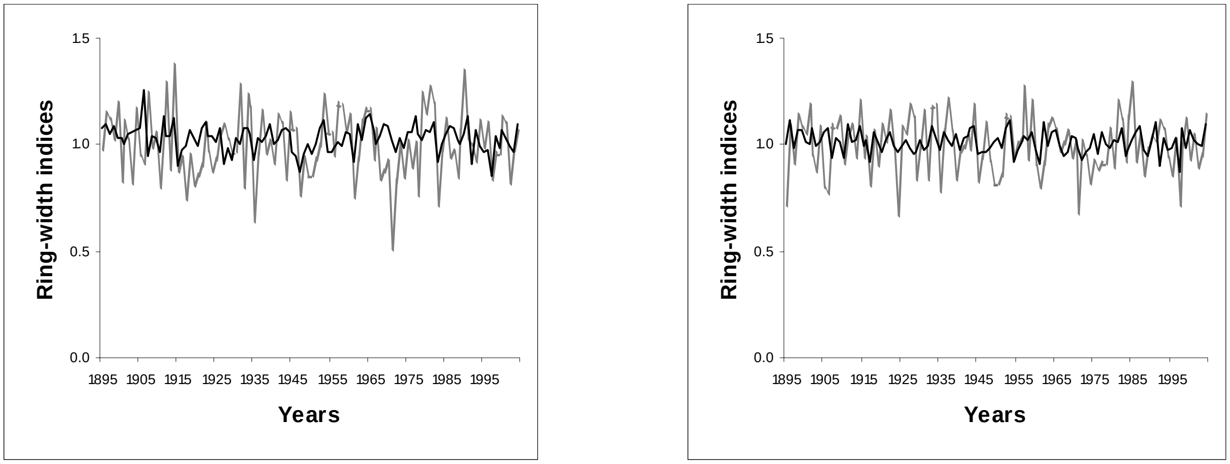
[c] Results from a significant sign test show reliable trends in the annual variability of the actual and predicted data.

Craggy Gardens **Big Bald**

a) 1896-1939 May-June calibration period



b) 1926-1969 May-June calibration period



c) 1970-2005 July calibration period

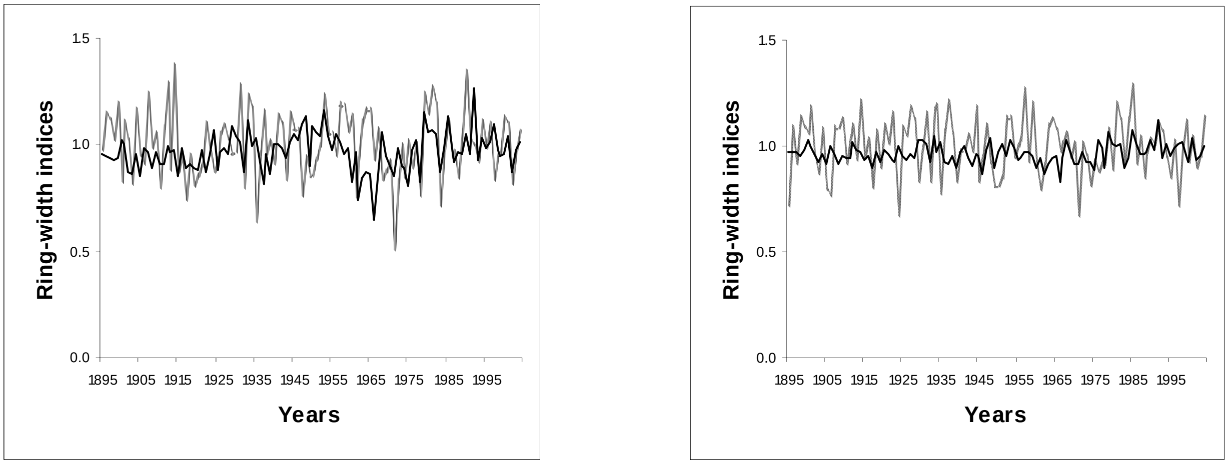


Figure 4. Predicted *Q. rubra L.* ring-widths from each multiple stepwise regression temperature model. The black line indicates the predicted ring-width and the dotted line indicates the actual ring-width for each residual chronology. a) 1896-1939 calibrated May-June models with verification periods 1940-1969, and 1970-2005. b) 1926-1969 calibrated May-June models with verification periods 1896-1925 and 1970-2005. c) 1970-2005 calibrated July model with the verification period 1896-1969.

Chapter 4

Chapter 2 Summary

This research provided a window into past environmental conditions and changes on two southern Appalachian balds, Craggy Gardens and Big Bald. Through the study of tree-rings combined with belt transect sampling and GIS, I reconstructed tree advancement into Craggy Gardens (Chapter 2) and linked the patterns to changes in past land use and associated disturbance. The more open oak woodlands of the early 1900s and before appear to have been related to the deleterious effects of livestock grazing on *Q. rubra L.* establishment and survival. After governmental acquisition of Craggy Gardens in the early 1930s and consequent cessation of grazing, red oaks increased dramatically until the 1960s, followed by a decline in encroachment from the 1970s that has lasted to the present. The decline in establishment is mainly a result of the ecological restoration efforts at Craggy Gardens aimed at maintaining the grass- and heath-dominated condition of the bald for its scenic quality and the conservation of rare and endangered species. This management aimed at reducing tree encroachment represents a new human disturbance further altering the successional development of vegetation at Craggy Gardens.

Southern Appalachian balds were most likely historically grazed by bison, elk, and deer with possible confounding Amerindian disturbances such as fire. However, by the arrival of Europeans in the 1800s, these historical grassland-grazing relationships were altered by land uses of an increasing population. The trend continued into the 1900s with widespread logging, human-set fire, and intensive livestock grazing heavily impacting the southern Appalachian Mountains (Pyle 1988). By the mid 1900s, public outcry regarding more than a century of land degradation resulted in governmental land purchases in the southern Appalachians set aside for both wise-use resource management and public recreation (Pyle 1988). With such shifts in land use, came a recovery in all ecosystem types in the southern Appalachians including balds. With the cessation of land use in balds after the 1930s, a lack of disturbance led to the expansion of woody vegetation over the next 75 years in many sites. This integrative analysis of Craggy Gardens supports the conclusions of other studies (Lindsay and Bratton 1979, 1980; Sullivan and Pitillo 1988; Johnson 1992; Weigl and Knowles 1995; Copenheaver et al. 2004, 2005) indicating that past land use and disturbance is and has been an important driver of vegetation dynamics in southern Appalachians grass balds.

Chapter 3 Summary

The dendroclimatic analysis of *Q. rubra L.* (Chapter 3) showed the influence of annual, inter-annual, and decadal drought and temperature variability on *Q. rubra L.* growing at its elevational distribution limit. *Q. rubra L.* tree-ring chronologies spanning two centuries from both Craggy Gardens and Big Bald (35 km apart) were analogous in their climatic response. Calibration of instrumental climate data with annual ring-width revealed that the prior year’s spring temperature is the principal variable for growth, but extreme drought variability can the override the temperature response in years where there is a lack of water availability. Regression modeling using moving window and stepwise procedures revealed that prior year’s spring temperature has been a consistent response for *Q. rubra L.* over the past 100 years, but that a shift and/or additional response to current summer temperature is apparent over the past four decades.

A lack of sample depth of old trees (>100 years) and the complexities in *Q. rubra* L. climate-growth associations in this study precludes a spring temperature reconstruction extending back to the late 1700s, but even so, it is likely that prior year’s spring climatic conditions were important in governing annual tree growth over the past two centuries. With an observed increase in temperature, based on the instrumental record over the past century and a positive response of *Q. rubra L.* to temperature circumstantial evidence suggest that 100 years of warming has enhanced *Q. rubra L.* growth at its tolerance range. Tree-ring evidence suggests a profound effect on the southern elevational distribution limit of *Q. rubra L.* over the past two centuries. The shift in *Q. rubra L.* temperature response over the past four decades suggest regional or even a documented hemispheric warming phenomenon (Briffa et al. 1998a, 1998b) may be responsible for *Quercus rubra* L-climate growth change. Several authors have found shifts in climate-tree growth associations over the past four decades across several species in differing geographic regions (for review see Briffa et al. 1998a, 1998b; Biondi 2000; Solberg 2002; Briffa et al. 2004; Carrer and Urbinati 2004; Wilson and Elling 2004; Wilson et al. 2004; Buntegn et al. 2006; Carrer and Urbinati 2006). However, conclusions cannot be made at this time regarding such trend in *Q. rubra L.*, but does provide inferred evidence to warrant chronology network expansion of *Q. rubra L.* growing at its elevational tolerance.

Several conclusions can be drawn from the Chapter 3 findings: 1) southern Appalachian balds are ideal sites for dendroclimatic studies in the southern Appalachian Mountains; 2) *Q. rubra L.* growing in these areas have a strong positive response to temperature and negative responses to drought; and 3) shifting associations between climate and *Q. rubra L.* growth suggest that climate changes over the past four decades could have possible implications for *Q. rubra L.* encroaching in high elevation ecotones in the southern Appalachians.

Conclusions

It is clear that both land-use and management activities have been important agents of vegetation change at Craggy Gardens effecting local-scale environmental change. This analysis supports findings of other studies, but we must take care not to extrapolate these finding to other balds. Each southern Appalachian bald has a unique land-use and disturbance history, which may require site-specific study to document. However, the methodologies used in this study could be applied to other balds in order to compile a regional understanding of both human impacts and ecological processes of southern Appalachian balds.

This thesis confirms that dendroecology and dendroclimatology methodologies are invaluable when investigating both the ecological and climatic processes of southern Appalachian high-elevation forests and balds. Combining tree ring study with GIS allows for spatial visualization and analysis that enhances interpretations. Transforming tree ring data into geographic datasets represents a technique not widely employed in tree ring research; however, with more exploratory studies, it may become an informative supplement for verification of findings.

This study has provided a scientific basis for understanding historical southern Appalachian bald dynamics and climate-tree growth relationships in these high elevation ecotones. Such research could be expanded to other southern Appalachian balds and high elevation forests to build larger datasets with older records of historical climate and environmental change in the southern Appalachian Mountains.

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Vita

Christopher John Crawford

Christopher Crawford is the first son of Bobby and Sandra Crawford and sister to Kelly Crawford Norville. He was born in Roanoke, Virginia on November 10, 1980. Along with his family, he lived in Roanoke, Virginia till 1988 before moving to Boones Mill, Virginia. He received his high school diploma in 1999 from Roanoke Valley Christian School in Roanoke, Virginia.

Christopher attended Carson-Newman College, Jefferson City, Tennessee in 1999 to play Division 2 college soccer. He was an undeclared major because of his interest in several fields of study. After taking courses in geology and sociology and coupling it with the curiosity of the outdoors during recreational hobbies, he decided to pursue study in the field of forestry. In 2000, he returned to Virginia and lived with some high school friends in Blacksburg and attended New River Community College. With an interest in pursuing forestry, he tailored his coursework to satisfy transfer requirements into a forestry program. Christopher was accepted into the forestry program at the University of Tennessee, Knoxville and began a B.S. in forestry resource management in 2001.

Building on his interest and fresh start in Knoxville in 2001, he began a career in environment and natural resources that would prove to change the course and direction of his life. He found the field of forestry exciting, challenging, and outdoor friendly. With considerable travel to various parts of United States during forestry and ecology coursework, he began to grasp a spatial context for forest, humans, and their interactions. During his final two semesters at Tennessee, the courses forest policy and natural resource organizational management and leadership taught by Dr. Dave Ostemerier had a monumental impact on his life would set the tone for future endeavors in natural resources.

Throughout his studies at Tennessee, Christopher worked in a variety of capacities in natural resources. In the years 2001 and 2002, he worked as a research technician for Dr. Scott Schlarbaum and Tennessee Tree Improvement. He worked on various research projects throughout Tennessee, Georgia, and Kentucky including a summer position at Mammoth Cave National Park inventorying the endangered hardwood Butternut **(***Junglans cinera L.*). In the summer of 2003, he took an internship position with the US Forest Service in Carbondale, Colorado. He served as forestry technician on the White River National Forest fulfilling the duties of forest health inventory, insect and disease surveys, timber management preparation, and wildland firefighting. With completion of his B.S. in forestry resource management from the University of Tennessee in 2004, he accepted a forestry technician position with the US Forest Service on the Salmon-Challis National Forest in Salmon, Idaho. He would live there until the fall of 2005. He held two separate positions in Salmon including Timber and TSI technician, and Fuels technician. He gained valuable experience in forest management including timber management preparation, implementation of silvicultural management plans, prescribed fire management, wildand firefighting, and GPS and GIS uses. At this point, with his travel, knowledge of environment, forest, and natural resources, and the observations of human impact, he wanted to understand the temporal and spatial connectivity of natural and human systems. This came with an understanding that GIS skills would become imperative for future career opportunities. With wise council from close friends, professors (especially Dave Ostemerier, Ph.D.), and family, he decided to pursue a M.S. in geography.

With acceptance into the Virginia Tech Graduate School and Department of Geography in fall of 2005, he would begin his research career in physical geography and biogeography. He found graduate coursework in geography exciting, thought provoking, and technical. Understanding the research environment from past experience, he quickly decided to work on a project with Lisa Kennedy, Ph.D. on globally rare southern Appalachian grass/heath balds using dendroecology, dendroclimatology, and spatial analysis (GIS) techniques. This was the quintessential master's research project and a perfect fit for his educational and professional background and new found love for geographic thought. His dedication to research and defense of a M.S. in geography on April 6, 2007 is a culmination of all the above experiences and education.

Christopher intends to pursue his Ph.D. within two years with an emphasis in climatology and paleoclimatology to test for the validity and reliability of proxy based climate reconstructions; in addition to understanding how past and present climate changes have affected and will affect forest and its human inhabitants.