Atlantic White Cedar: Ecology, Restoration, and Management

Proceedings of the Arlington Echo Symposium

Millersville, Maryland

June 2–4, 2003

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Cover photos: Aerial photos (1,000-foot altitude) of the Penn Swamp clearcut in Wharton State Forest, New Jersey, and the site of the subsequent deer-slash experiment: 1990 (top photo, as clearcut was being finished), 1995 (middle photo), and 2000 (bottom photo).

Photos and cover design by George Zimmermann.

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Preface

I am pleased to write this preface to the proceedings of the symposium on Atlantic white-cedar (AWC) held at the Arlington Echo Outdoor Education Center, Millersville, MD, in June 2003, chaired by Keith Underwood and Philip Sheridan.

The theme of the symposium was "Uniting Forces for Action," and it was clear that the attendees were indeed united in their desire to study this globally threatened species, gain a more holistic view of the AWC ecosystem, and cooperate to insure that the scientific work so ably done here and elsewhere translates into action to restore and responsibly manage AWC.

More than 15 papers and a number of posters were presented during the symposium, and the attendees were able to view AWC sites, including a number of restoration sites. I was very impressed by the State of Maryland's use of educational facilities such as Arlington Echo. These facilities have been used to give Maryland's citizens (especially the children who in turn have educated and motivated their parents) a sense of their connection to the environment and the need for their help and stewardship in restoring AWC. Symposium attendees from other States can take home valuable lessons about environmental education.

Participants in the symposium came from throughout the range of white cedar, from New England to the Gulf coast. There is no doubt that this species, extirpated in many areas, has captured the attention and scrutiny of many researchers and other highly motivated individuals.

This publication includes a representative subset of the papers presented at the symposium. Laderman and Domozych's paper expands our knowledge of other life forms inhabiting AWC habitats—a fundamental step in understanding the ecosystem as a whole. Papers by Crawford and others, Derby and Hinesley, Mylecraine and others, Hopton and Pederson, and Gengarelly and Lee give us more data on the physical aspects of white-cedar ecosystems and in some instances their interaction with the biological factors. These papers present information that will help us restore and understand AWC and their functioning.

The range, restoration, and stewardship of AWC ecosystems are discussed in papers by McCoy and Keeland, Underwood and others, and Broersma-Cole. We also present the first of numerous papers by Mylecraine and others that have given us vital information on range-wide AWC genetics, and finally a paper by Zimmermann and Mylecraine that discusses the long-term effects of various silvicultural manipulations on the entire vegetation community.

I hope that all of the papers and posters presented at the symposium will eventually find their way into the literature; they all contained information important to our understanding of the species, its continued restoration, and wise management across its range.

George Zimmermann
Professor of Environmental Studies
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Contents

CLIMATE SENSITIVITY OF ATLANTIC WHITE CEDAR AT ITS NORTHERN RANGE LIMIT

H. Myvonwynn Hopton and Neil Pederson[1]

Abstract—Atlantic white cedar is a wetland tree species with ecological and commercial importance that is distributed primarily along the Atlantic seaboard to south central Maine. The number of AWC swamps has declined due to human impacts. The potential for rapid climate change and AWC's threatened status make it important to study factors affecting its growth, especially climate. The objectives of this study are to determine the usefulness of AWC for tree-ring analysis, its sensitivity to climate along its northern range limit, and to study its growth rates. Seven AWC populations from northern New Jersey to southern Maine were found to be sensitive to changes in its environment. Growth was most commonly correlated to prior May and June, winter through spring, and current July and August temperatures. Decadal variations in temperature closely mirror variations in AWC growth suggesting that temperature is the primary limiting factor across the region from 1902 to 1995.

Keywords: Climate change, northern range limit, temperature, tree growth, tree productivity.

INTRODUCTION

Atlantic white cedar (AWC), [*Chamaecyparis thyoides* (L.)] ecosystems in the Northeastern United States are deemed threatened because of their rarity in the landscape. New Jersey's AWC population has decreased 74 percent from its estimated historic area (from 47,000 ha down to 12,100 ha) (New Jersey Department of Environmental Protection 2003). In the glaciated Northeast, only 5,300 ha of AWC swamp remain (Motzkin 1991). The primary causes of their net loss over the last two centuries are logging and habitat destruction (Laderman 1989).

Atlantic white cedar is important commercially and has been heavily logged since colonial times because of its workability and resistance to decay and insects. AWC has been historically used for shingles, barrels, and boats. Today it is still an important commercial tree in New Jersey, Virginia, the Carolinas, and Florida, and is often used for telephone poles, piling, ties, and siding (Little and Garrett 1990).

Atlantic white cedar ecosystems are ecologically important because they provide unique cover, habitat, and food for a variety of fauna. For example, a plant survey of a recently discovered AWC community in west central Georgia contributed significantly to the knowledge of rare plant occurrence within the region (Sheridan and Patrick 2003). The larva of the endangered Hessel's Hairstreak butterfly (*Callophrys hesseli* Rawson and Ziegler) feed solely on AWC leaves in Maine (Kluge 1991). White-tailed deer (*Odocoileus virginianus* Boddaert) preferentially eat AWC seedlings as a food source (Dickerson 2002). Therefore, studying, protecting, and managing AWC ecosystems is beneficial both for commercial and ecological reasons.

Atlantic white cedar grows along the Eastern Coast of the United States no more than 130 miles inland, with its northern range limit in south central Maine (Little and Garrett 1990). Because of its economic and ecological value and threatened status as an ecosystem, it is important to understand what factors limit the growth of AWC for future management and conservation. Studying AWC's climatic sensitivity is especially important in the face of potential rapid climate change although the species is not traditionally used in dendrochronological research. Nevertheless, Golet and Lowery (1987) found that changes in measured relative ring width could be explained by variations in water level in several Rhode Island AWC swamps. However, they concluded that their findings were wetland specific without a strong regional climatic signal. Pederson and others (2004) found AWC to be very temperature sensitive in southern New York State and northern New Jersey region. It is not known if this sensitivity can be extended to a regional scale.

The objectives of this study were to: (1) identify how well AWC crossdate (agreement in population's annual radial growth variations), (2) improve our understanding of the climate response of AWC, and (3) study its growth over the last 100 years. Specifically we tested whether the trees along their northern range limit show sensitivity to climate and if so, which climatic variables account for variations in annual ring widths. Although not often tested in temperate regions, it is thought that trees are more sensitive climatically at range limits. Research on loblolly pine (*Pinus taeda* L.) indicates that cool temperatures only became a growth-limiting factor at its northern range limit (Cook and others 1998). Therefore, we hypothesized that radial growth at the northern range limit for AWC was most limited by temperature of the previous and current growing season.

PROCEDURE

Increment cores were collected from seven different sites along the northern edge of Atlantic white cedar range limit:

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Appleton Bog, ME, Saco Heath, ME, Westminster, MA, Monson, MA, North Madison, CT, High Point, NJ, and Uttertown, NJ (fig. 1). To characterize forest composition at each site, four measurements of basal area (BA) using a cruise prism were taken at every fourth or fifth tree cored and averaged. Here we report only those species making up > 10 percent of stand BA (table 1).

Cores were collected and processed using standard dendrochronological techniques (Fritts 1976, Stokes 1968). Dr. Thomas Siccama and his students at Yale University collected cores from North Madison Cedar Swamp, Connecticut in 1988, 1991, and 1992. The cores were loaned to the Lamont-Doherty Tree Ring Lab for this study. Basal area measurements were not available for this site. From each of the other sites, cores were collected from at least 20 different trees using a hand-operated increment borer, except for Monson, MA due to its lack of old trees. Since climate response was the focus of this study, healthy dominant older looking trees were selected for coring so as to maximize the climate response. This non-random selection may not fully represent the stand-level climate response. However, some research suggests that competition can obscure the temperature signal in trees (Cescatti and Piutti 1998). Also, trees in declining health may be unresponsive to climate. Therefore, in keeping with the study's main goal we avoided sampling understory or unhealthy appearing trees. To maximize the geographic coverage while minimizing field and laboratory time, a single core was taken from each tree sampled. A second core was occasionally taken if the tree appeared old to increase sample replication and strengthen the cross-dating. This is less than the typical tree ring protocol of two cores per tree. However, tree replication is more efficient than core replication in reducing estimated mean standard error (Fritts 1976). Once the cores were extracted, they were stored in labeled plastic straws for transport back to the Lamont-Doherty Tree Ring Lab, Palisades, NY.

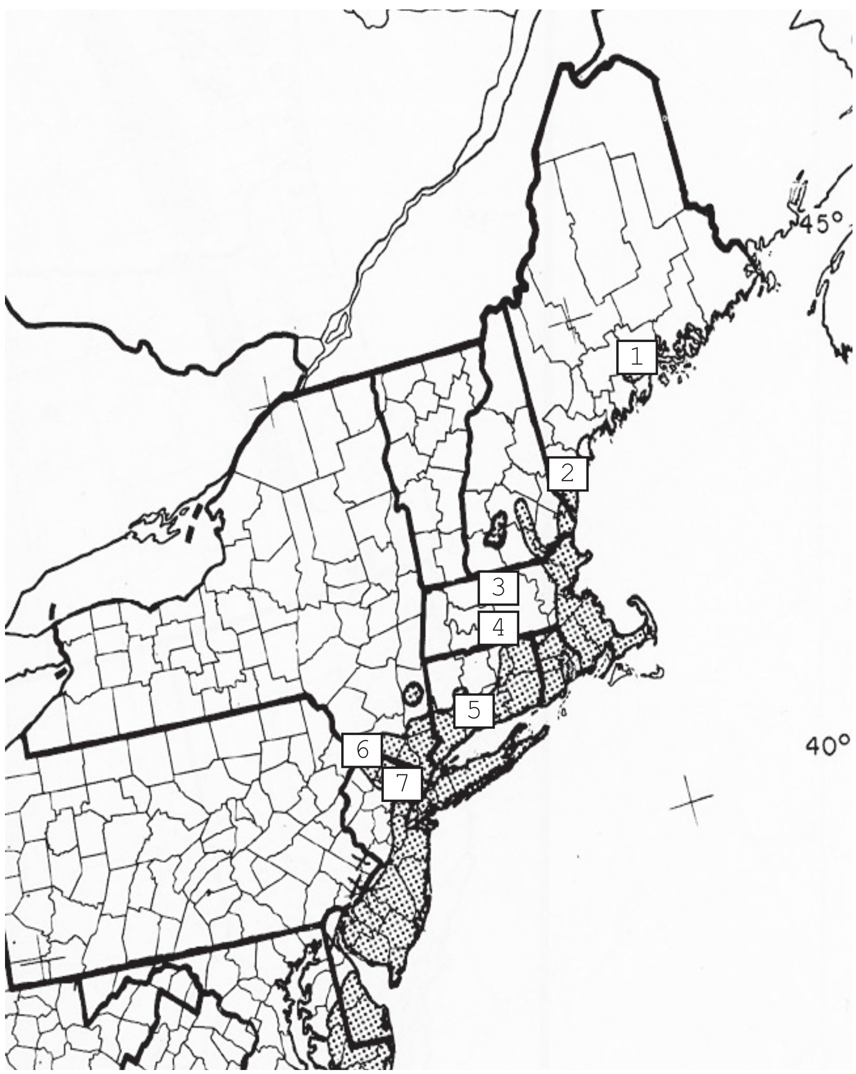

Figure 1—Atlantic white-cedar populations sampled in the Northeastern United States: 1 - Appleton Bog, ME; 2 - Saco Heath, ME; 3 - Westminster, MA; 4 - Monson Cedar Swamp, MA; 5 - North Madison Swamp, CT; 6 - High Point, NJ; 7 - Uttertown Bog, NJ. Stippled area represents the northern distribution of Atlantic white-cedar as adapted from Little (1971).

Table 1—Site information for the Atlantic white cedar stands sampled

Site	County	Latitude/longitude	Elevation	Stand BA (STD)
			m	*m²/ha*
Appleton Bog, ME	Knox	N43°33' W70°28'	120	66.0 (15.3)
Saco Heath, ME	York	N44°20' W69°16'	40	35.5 (24.0)
Westminster, MA	Worcester	N42°32' W71°57'	250	47.3 (22.8)
Monson, MA	Hampden	N42°03' W72°18'	260	48.0 (6.9)
Madison, CT	New Haven	N41°21' W72°38'	80	—
High Point, NJ	Sussex	N41°38' W74°39'	460	54.8 (17.9)
Uttertown, NJ	Passaic	N41°10' W74°25'	300	79.2 (15.7)

BA = basal area.

At the lab, the cores were air-dried and then glued to wooden mounts. The cores were sanded with increasingly finer sandpaper up to 600 grit. The cores were then examined under a microscope and visually cross-dated. Rings were measured to the nearest 0.001 mm. Visual cross-dating was verified using the program COFECHA (Holmes 1983). Correctly dated time-series of growth were standardized using a double detrending method with the intent to preserve as much low frequency information as possible unrelated to competition (Cook and Kairiukstis 1990). First, a negative exponential curve or linear regression was used to remove geometric growth trends caused by the narrowing of rings as stem diameter increases. If a step change in growth was observed, a second detrending was done using a two-thirds spline to remove increases in growth related to changes in local competition (Lorimer and Frelich 1989). Standardized ring widths were then averaged to create an index of growth for each site.

Chronology signal strength was characterized using series intercorrelation (SNC) and the between tree expressed population signal (EPS). SNC indicates the strength of the common signal within a sample population and is derived from the correlation between all time-series of growth. EPS is a function of the mean correlation of all growth series within a population and sample size (Wigley and others 1984). It describes how well a finite sample size estimates the infinite, hypothetical population. These statistics are among the most commonly used indicators of agreement in year-to-year growth among trees within a population (Cook and Kairiukstis 1990).

The climatic sensitivity of each population was found by correlating the standardized ring index chronology against mean monthly temperature and total monthly precipitation from prior March to October of the current growth year. We chose a 20-month period of climate for correlation analysis as climate of the prior year can influence ring width of the current year (Fritts 1976). Because long-term meteorological records of minimum and maximum temperatures are lacking in the Appleton Bog region of ME, we chose to use gridded meteorological data from the Climatic Research Unit (CRU) of the University of East Anglia, UK (Jones 1994, New and others 2000). Grid points are located every 0.5 degrees and are interpolated climatic data from the eight nearest stations. For our purposes, data from the grid point closest to the sample site was used. Data is available from 1901 to 1995. Correlations were considered significant at $p \leq 0.05$ unless otherwise stated.

Regional Temperature and Growth Trends

To test if the climate signal in AWC is potentially regional, we compared a time-series of regional temperatures with a time-series of regional growth. Using CRU data, the months of temperature most commonly correlated to growth (prior May and June, prior November though current May and current July and August) were averaged using a mean and variance corrected arithmetic average procedure. This time-series covers 1902 to 1995 because 1 year is lost due to the combination of months from the prior and current years (e.g. May, June, November and December 1901 combined with January to May and July and August 1902). An arithmetic average was made of the standardized chronology of each population to create the regional time-series of growth.

RESULTS

Appleton Bog, ME

Appleton Bog is unique in that it is the northernmost known stand of AWC (Stockwell 1999). The forest floor is covered with *Sphagnum* moss and fern species. AWC dominates the canopy, comprising 77.3 percent of the basal area (BA), with occasional red maple [*Acer rubrum* L. (13.6 percent)] and black spruce [*Picea mariana* Mill. (12.5 percent)] present. Maximum tree age was 141 years with more than one-half of the trees older than 119 years (table 2). The SNC was r = 0.616, which is well above the 99 percent confidence level of 0.328 (Holmes 1983). EPS value for the Appleton Bog chronology was 0.929, which is above the accepted level of 0.85 (Wigley and others 1984). The standardized ring index chronology showed below average growth in the early 1920s and 1960s while above average growth occurred in the mid-1920s through the mid-1950s and from the mid-1970s until the mid-1990s (fig. 2A). Appleton Bog AWC was positively correlated with temperature during the prior May, June, September, November, and current January through April (table 3). These months accounted for 29.6 percent of the ring width variations. Only 3 months show positive correlation with precipitation: prior August, current March and July accounted for 8.80 percent of the growth variation.

Saco Heath, ME

Saco Heath is the only known domed-bog to support AWC (Laderman 1989). Saco Heath is composed of scattered aggregations of trees through out a dense shrub layer dominated by blueberry (*Vaccinium* spp. L.). In the forested areas, AWC is the dominant tree comprising 82.9 percent of the BA, while white pine (*Pinus strobus* L.) is present to a lesser extent at 12.7 percent. Maximum tree age at Saco Heath was 129 years with more than one-half of the trees older than 100 years (table 2). The SNC was r = 0.567 while the EPS was 0.933. The ring index chronology had growth trends similar to Appleton Bog. The early 1920s and 1960s were a decade of below average growth (fig. 2A). The low growth in the 1960s was followed by a period of unprecedented above-average growth that lasted to the present. March to August and November to December temperatures of the previous growing season, and January to February and April to August temperatures of the current growing season were positively correlated with growth (table 3) and accounted

Table 2—Statistical characteristics of the final Atlantic white-cedar chronologies[a]

Site	Trees	Cores	Interval	Median age[b]	Rbar	EPS	Number of samples EPS = 0.85	Date when sample depth = 0.85 EPS[c]
	- - - *number* - - -		*years*	*min/max*				
Appleton Bog, ME	21	29	1862 – 2002	119 (63/141)	0.375	0.929	10	1879
Saco Heath, ME	20	30	1874 – 2002	100 (69/129)	0.583	0.933	5	1879
Westminster, MA	26	29	1859 – 2002	111 (82/200)	0.378	0.922	10	1887
Monson, MA	16	17	1865 – 2002	116 (53/138)	0.531	0.926	5	1870
Madison, CT	21	22	1819 – 1992	142 (92/174)	0.608	0.974	4	1831
High Point, NJ	20	31	1807 – 2002	150 (104/196)	0.393	0.936	9	1830
Uttertown, NJ	20	20	1762 – 2002	125 (72/242)	0.257	0.863	17	1897

EPS = expressed population signal.

[a] Rbar is the average correlation between all trees. EPS is the expressed population signal. See text for more details.

[b] Tree ages are likely higher than shown since several sites had some rot, especially Westminster, MA and High Point, NJ.

[c] This column refers to the date when the sample depth equals the number of cores required to reach an EPS value of 0.85 for each chronology. Before this date, sample depth declines and it is expected that the EPS value would drop below 0.85.

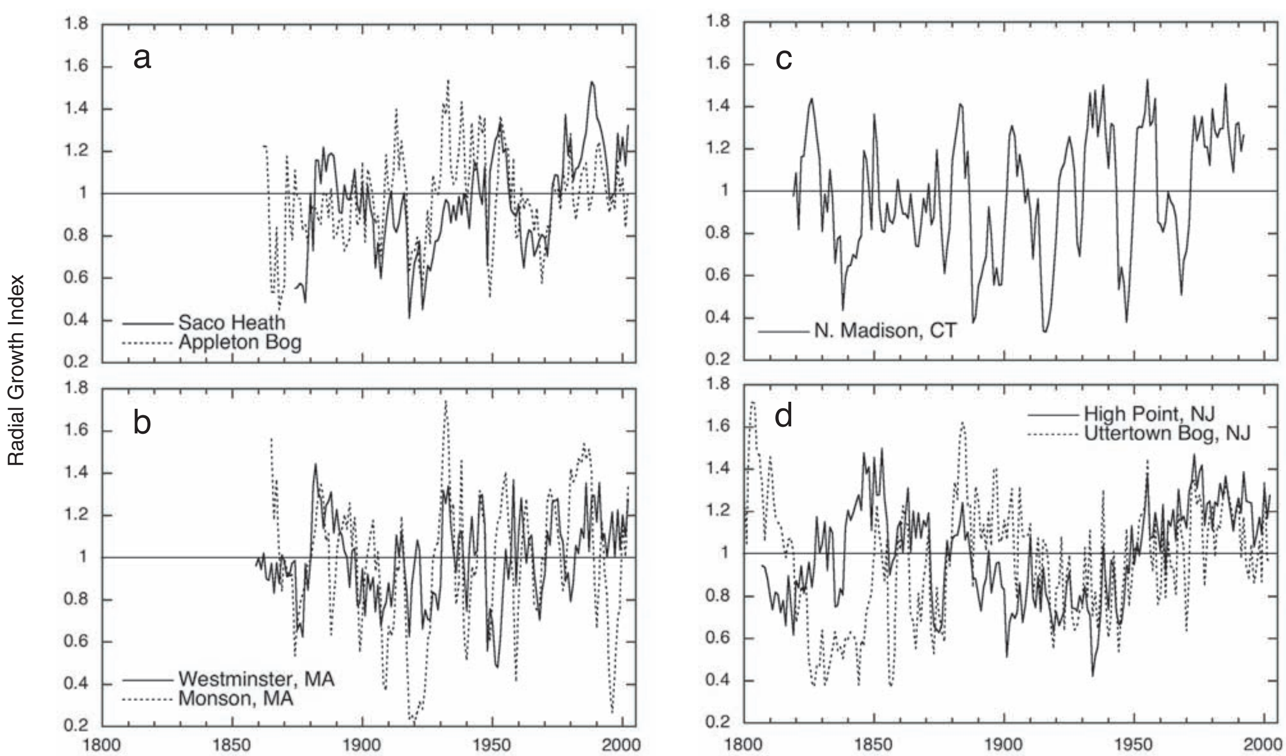

Figure 2—Standardized radial growth chronologies for: (a) Maine (b) Massachusetts (c) Connecticut, and (d) New Jersey. See text for details of each site within each State. Growth is standardized about a dimensionless index of one represented by the horizontal flat line.

Table 3—Significant correlation between Atlantic white cedar growth and mean monthly temperatures

Site	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O
Appleton Bog, ME			**	**			**		*		**	*	*	*						
Saco Heath, ME	**	***	**	*	**	*			**	**	***	***		**	**	*	**	***		
Westminster, MA			**	**			**		**				*		*			*	*	
Monson, MA			**				*		*			*								
Madison, CT			**	**	*					*		*	*	*	*	*	*			
High Point, NJ		*				**			***	*	*	***		**			*	***		
Uttertown, NJ			*							*			**	*						
Number of sites with significant correlation	1	2	6	4	2	2	3	0	5	4	3	5	4	5	3	2	3	3	1	0

* = a significant relation between 0.01< and < 0.05; ** = significance between 0.001< and ≤ 0.01; *** = significance between < 0.001.

for 44.46 percent of the annual growth variation. Growth at Saco Heath was also positively correlated to mean monthly precipitation data for August and November of the previous growing season, and March to April and August of the current growing season. These months accounted for 27.68 percent of the growth variation.

Westminster, MA

The Westminster forest is comprised of AWC (60.3 percent BA), tamarack [*Larix laricina* (Du Roi) K.Koch (38.1 percent)], red maple (16.9 percent), and red spruce [*Picea rubens* Sarg. (14.8 percent)]. Maximum tree age in this population was 200 years with more than one-half of the trees older than 111 years (table 2). The SNC was r = 0.565 while the EPS was 0.922. Radial growth was generally below the average value between the 1900s and the mid-1950s (fig. 2B) and above the average value after the 1950s. Growth of the Westminster population was positively correlated to the previous year's May to June, September, and November temperatures, as well as current March, May, August, and September temperatures (table 3). Growth was positively correlated with precipitation of the current July and September. Temperature accounted for 30.54 percent of ring width variation, while precipitation accounted for 11.23 percent.

Monson, MA

At Monson, AWC comprises 42.2 percent of the BA, with 25.0 percent red spruce, 25.0 percent eastern hemlock (*Tsuga canadensis* L.), 18.8 percent eastern white pine (*Pinus strobus* L.), and 16.7 percent red maple. Monson has field evidence of logging within the last 70 years. Maximum tree age at Monson was 138 years with more than one-half of the trees older than 116 years (table 2). The SNC was r = 0.622 while the EPS was 0.926. Radial growth was generally below average growth from the 1900s to the mid-1950s (fig. 2B). The radial growth index showed a period of decreasing ring width from the 1890s to the early 1920s. Growth from 1970 through the mid-1980s was above average and has since decreased considerably. Growth in the Monson AWC population was positively correlated to the prior year's March, September, November and current February temperatures (table 3) and accounted for 16.37 percent of the ring width variations. Only a wet prior November was correlated to growth and accounted for 4.02 percent of the annual growth variation.

North Madison Cedar Swamp, CT

The North Madison Cedar Swamp is a late-successional bog-forest dominated by AWC, with scattered red maple (Andrews and Siccama 1995). Maximum tree age in the North Madison Cedar Swamp was 174 years with more than one-half of the trees older than 142 years (table 2). The SNC was r = 0.616 while the EPS was extremely high at 0.974. Radial growth was below average from the 1840s through the early 1920s, after which growth was above average except for a dip in the 1960s (fig. 2C). Growth in the North Madison AWC population was positively correlated to prior May to July and December, and current February to July temperatures (table 3). These months accounted for 19.49 percent of annual growth variations. A wet current October was positively correlated to growth accounting for 5.71 percent variance in ring width.

High Point State Park, NJ

High Point's AWC population is growing at the highest recorded elevation for the species (Laderman 1989). AWC makes up 73.9 percent of the total BA with eastern hemlock (13.7 percent) and red maple (10.9 percent) as the next most dominant trees. Maximum tree age in the High Point was 196 years with more than one-half of the trees older than 150 years (table 2). Several of these trees were hollow, and this prevented analysis of growth in older wood. Hence, age structure is a bit older than what can be reported here. The SNC was r = 0.549 while the EPS was 0.936. The standardized chronology shows a decline in ring width from the 1850s until the 1950s, after which ring width was above average (fig. 2D). This population was very sensitive to temperature (table 3), and growth was positively correlated to prior April, August, November, December, and current January, February, April, July and August. Temperature accounted for 37.54 percent of the ring width variation. Only 2 months, May and November of the prior growing year was positively correlated with precipitation and accounted for 11.43 percent of the ring width variation.

Uttertown Bog, NJ

Uttertown Bog is one of New Jersey's few remaining peatlands (Kuo 2003). AWC represents 80.3 percent of the BA, with eastern hemlock representing 18.0 percent. Maximum tree age in Uttertown Bog was 242 years with a majority of the trees between 110 and 140 years old (table 2). The SNC was r = 0.566 while the EPS was only 0.863. Radial growth increased from the 1860s until the 1910s, followed by a period of decline until the 1950s (fig. 2D). Following a slight dip in the 1960s, growth has increased since the 1970s. Uttertown was one of the least climate-sensitive populations studied here. Prior April and December and current January and April temperatures were positively and significantly correlated to climate (table 3) accounting for only 10.07 percent of the ring width variation. Prior May and December and current May and June precipitation were significant and positively correlated to growth. Precipitation accounted for 13.88 percent of the variation in ring width.

Regional Temperature and Growth Trends

There was a strong agreement between regional temperature and AWC growth (r = 0.66; $p < 0.0001$) from 1902 to 1995 with temperature accounting for 42.9 percent of variation in growth. The agreement is especially evident at decadal time scales (fig. 3).

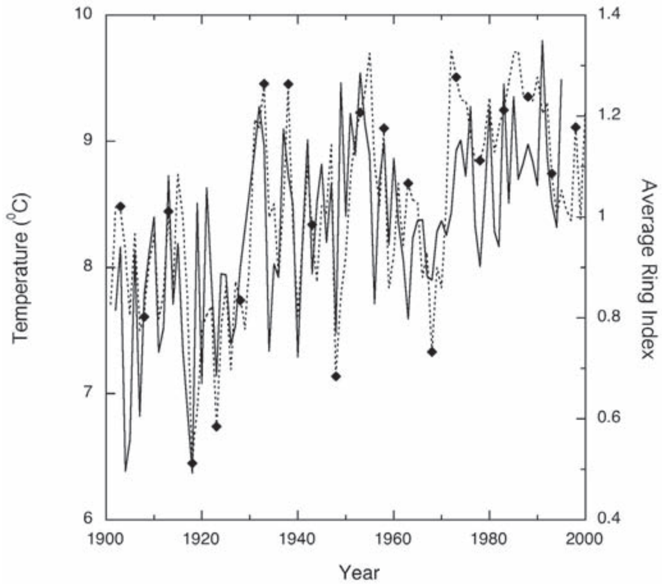

Figure 3—Regional temperatures (solid line) versus regional standardized growth of Atlantic white cedar (dashed line with solid diamond symbols). See text for further details.

DISCUSSION

Usefulness of AWC for Dendrochronology

Our results show that AWC growth is very sensitive to environmental conditions, making it useful for tree-ring analysis. The between-tree EPS was high (> 0.920) in six of the seven populations and suggests a strong common signal. Though not the focus of this study, individual trees from several populations showed possible release from competition that was likely related to canopy disturbance. Standard disturbance detection methods may be used to reconstruct stand history using AWC (Lorimer and Frelich 1989).

The primary limitation for the dendroclimatological use of AWC at the sites studied is its current age structure. Most stands sampled were < 130 years in age. The Uttertown site appears to be essentially an even-aged 120 year-old forest with a few scattered old trees. North Madison, CT and High Point sites had the least disturbed forests of the sites studied and yet no trees older than 200 years were found. If available, sub-fossil or relict wood samples could be analyzed in an attempt to extend stand disturbance history and chronology length. Given AWC's responsiveness to environmental variation, it is likely worth the effort and expense of relict wood recovery. Such a collection would greatly enhance our knowledge of long-term climate variability and AWC ecology in a heavily populated region, which may be useful for restoration of AWC ecosystems.

Climate Response

In general, AWC has a positive correlation to temperature at its northern range limit (fig. 4). Across all sites the monthly temperatures most frequently correlated with growth were prior May and June, prior winter through current spring (November to May), and current July and August temperatures (table 3). The strongest correlations between growth and temperature were during winter months. More than one-half of the sites sampled had levels of temperature sensitivity similar to the trees used for the only Eastern United States temperature reconstruction (Conkey 1982). Temperature accounted for 29.6 percent or more of annual growth variation at four sites making AWC one of the most temperature sensitive trees in the Eastern United States.

Of the sites sampled, correlations were strongest at Saco Heath, Appleton Bog, and Westminster Swamp, indicating that temperature is most important near the northernmost end of AWC's range limit. More southerly populations at North Madison and Uttertown had a lower sensitivity to temperature variation. These results are similar to the temperature

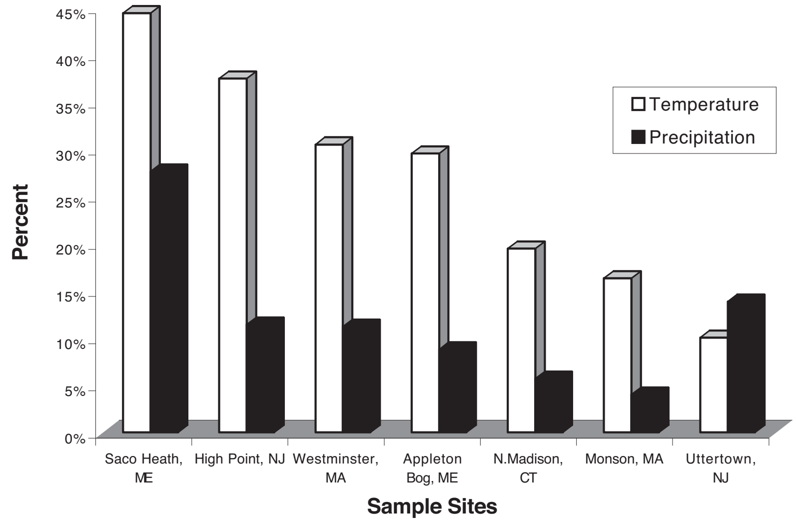

Figure 4—Sites are listed from left to right in the order of decreasing temperature sensitivity. The y-axis represents the amount of annual ring width variation that can be accounted for (r-squared) by temperature (open bars) and precipitation (black bars). See text for further details.

sensitivity for growth documented previously for loblolly pine (Cook and others 1998).

High Point, NJ is an exception to the geographic trend in temperature sensitivity. While High Point was one of the more southern sites sampled, AWC growth was one of the most sensitive to climate, but this population is growing at the highest known elevation for the species and likely experiences lower temperatures than other populations at that latitude. Using the CRU meteorological data, mean annual winter and summer temperatures from 1901 to 1995 for High Point fall close to those for Saco Heath, ME. Average summer and winter temperatures at High Point are 21.06 °C and -1.66 °C, respectively. At Saco Heath summer and winter temperatures averaged 20.06 °C and -3.66 °C. However, there is a significant difference between the elevation of the High Point AWC population (460 m) and the closest meteorological station most likely to have been heavily weighted in the CRU interpolation data (Point Jervis, NY, 143 m). Assuming an average environmental lapse rate of 0.65 °C cooling per 100 m in elevation, the mean summer and winter temperatures at High Point would actually be roughly 19.00 °C and -3.72 °C, respectively. Thus, the temperatures in which the High Point AWC trees live would fall within the range of temperatures of the Maine AWC sites, possibly explaining the exception in the geographic trend.

If AWC responds like other tree species, the reduced temperature sensitivity of populations at more southern sites may be the result of location in the species' range (Cook and others 1998) or greater competition with other plants (Cescatti and Piutti 1998). The current age structure at the Monson site suggests stands are still in the stem exclusion stage during which competition induces self-thinning and excludes tree recruitment (Oliver and Larson 1996). As a result, stand development at Monson may be contributing to AWC's reduced temperature sensitivity at this site.

The Uttertown site was the only site where growth was more sensitive to precipitation than temperature. Also, it was the southernmost site sampled. In addition to a warmer climate than experienced by the more northern populations, increased competition may cause tree growth to be more limited by precipitation as was shown in another tree species by Cescatti and Piutti (1998). While the Uttertown site has the highest estimated BA of the sites sampled, it is similar to the BA of Appleton Bog, near the species' northern range limit. More work is needed to determine if stand densities (a proxy for competition) within one climate region has an influence on AWC's climate sensitivity.

It is interesting to note sites that showed the highest sensitivity to temperature also showed the highest sensitivity to precipitation (fig. 4). The Saco Heath population showed the greatest overall sensitivity to climate. Since Saco Heath is a domed-bog, a unique wetland type for AWC (Laderman 1989), perhaps the site's physical characteristics along with its range position made it the most sensitive to climate. A domed-bog results from the build up of peat over time, which eventually serves to elevate the area from its surroundings so that it is perched above the water table. Surface water does not drain into domed bogs, making precipitation the primary source of water. The physical structure of a domed bog and the resulting hydrological regime would seem to explain Saco Heath's high sensitivity to precipitation. Saco Heath's low stand density (table 1) could also have been a factor in the high temperature sensitivity, following the same logic in the previous paragraph.

Growth Trends

Most sites showed similar decadal variations in growth over the last century, especially over the last 30 years indicating a growth trend for the region (figs. 2 and 3). The recent period of common increased radial growth suggests large-scale influences on growth, such as climate, nitrogen deposition or elevated CO_2. Temperature seems the most plausible explanation for much of the last 100 years. A decline in regional growth trends during the 1960s (fig. 3) in concert with declines in regional and global temperatures (Jones and Moberg 2003) suggest temperature is controlling radial growth. In fact, the CRU meteorological data for our study region and Northern Hemisphere data show that winter and spring temperatures have been rising over the recent decades (Jones and Moberg 2003, Lugina and others 2003) suggesting temperature may be linked to increased radial growth in recent decades.

Minimum temperatures have increased more rapidly than maximum temperatures (Karl and others 1993), which may be an important attributing factor to the increasing growth trend. AWC research of populations in the southern New York State and northern New Jersey region suggests growth is consistently correlated with minimum July and August temperatures (Pederson and others 2004). To date, we don't know if this local sensitivity to growing-season minimum temperature occurs at the regional scale as well.

The Monson site remained the exception to general regional patterns, and had a sharp decline in growth over the last 15 years. The lack of synchronicity in the Monson population may again be attributed to its disturbance history or inadequate sampling for detection of trends.

CONCLUSION

Atlantic white cedar growth is sensitive to changes in its environment. All populations tested showed strong interseries correlation and EPS values, indicating that the trees are responding to a common signal in their environment. More importantly radial growth in AWC at its northern range limit was positively correlated with monthly mean temperature data over the prior and current year. Atlantic white cedar growth also was positively correlated with variations in monthly mean precipitation data, but correlations were not as strong. The sites most sensitive to temperature were also found most sensitive to precipitation.

The forecast of future climatic warming does not appear to pose any immediate threat to growth of this species along its northern range limit. If temperature trends proceed as expected increasing 1.7 to 4.9 °C over the next century (IPCC 2001, Wigley and Raper 2001), growth would likely increase assuming moisture availability does not become a more important limiting factor. This could have implications for future ecosystem management and carbon sequestration modeling. However, how climate change will influence relative competitive ability is unknown.

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