# DENDROCLIMATOLOGY ALONG CLIFF ENVIRONMENTS OF NORTHEASTERN WEST VIRGINIA: A COMPARISON OF RIDGETOP PINES AND CLIFF-LINE RED CEDAR

**Group Leader: Brendan Buckley**

Shawn Fraver, Ryan Hanson, Doug Harley, Rachel Hochman, Alison Murphy and Tomasz Wazny

## INTRODUCTION

Cliff environments can provide excellent locations for dendrochronological studies. This is largely due to harsh growing conditions that often result in an enhanced sensitivity to climate variability. The relative inacessability of such locations also reduces the chance of anthropogenic disturbance, such as logging and fire. Therefore, depending on the natural stability of a particular cliff environment, trees may attain very old age (i.e., > 500 years). Dead stems of conifers like *Thuja* and *Juniperus* can survive for many hundreds of years on ledges and talus slopes, making it possible to extend living chronologies by hundreds of years or more, prior to the time span of the earliest living trees.

The harsh conditions for plants growing on exposed, rocky cliff faces (e.g., water and/or temperature stress, poor nutrient availability, and restricted root growth) have been shown to produce climate sensitive records in trees (e.g., Kelley et al., 1992; Larson, 1997). In many cases, such trees are entirely dependant on atmospheric sources of water for all physiological processes. In the case of *Thuja occidentalis* growing on the Niagara Escarpment of Ontario (Kelley et al., 1992) radial growth is limited by high summer temperature. For *Juniperus virginiana* on the cliffs of Virginia, Larson (1997) found the limiting factor to be drought.

Severe growing-season drought can result in reduced radial growth for particular years, synchronous in all trees across a broad region. Such "pointer" years are likely to be indicative of a regional-scale climatic influence, and if the relationship between tree-growth and climate can be sufficiently modeled, reconstruction of climate patterns over centuries to millennia can be attained. For this study we update and compare two drought-sensitive tree-ring chronologies from cliff sites in northeastern West Virginia; one of *Pinus* spp. and one of *Juniperus virginiana*. These chronologies are based on both living and non-living material.

*The study premise*

As participants of the 10th North American Dendroecological Fieldweek (NADEF), held at The Mountain Institute on Spruce Knob, West Virginia, we sought to explore the dendroclimatology of the cliff environments around the Seneca Rocks region. First, we wished to update two existing, proven drought-sensitive, ring-width chronologies; Dairy King *Pinus* (DKP) and Cedar Knob *Juniperus* (CKJ). These sites were sampled during the late 1970s/early 1980s by Dr. Ed Cook (pers. comm.) and were consequently more than 20 years out of date. The past two decades have experienced some unusual climate changes. An update of these chronologies was therefore considered crucial for a more robust climate calibration, due to the addition of 20 years to the period of comparison. Second, we hoped to expand the chronologies further back in time, through the addition of subfossil samples found along the cliff faces and in the talus below the cliffs. This backward extension of climate-sensitive tree-ring time series is vital to a more complete understanding of the natural variability of climate.

*Study sites*

Both study sites are located within the Allegheny Mountain section of the Allegheny Plateau physiographic province. Ridges within this part of the Province consist of Paleozoic sandstones and conglomerates (Stephenson 1993). The Plateau is typified by southwest-to-northeast ridges, several exceeding 1300 meters. Our two study sites are within 17 km of Spruce Knob, West Virginia (elev. 1482 m.), at circa 37˚ 40'N. Annual precipitation at these elevations may exceed 142 cm (Stephenson 1993).

The DKP site is located on the summit of an exposed sandstone ridgeline which rises 50 to 100 meters above a steep talus slope. The CKJ site consists of a calcareous sandstone escarpment on the southern flank of Cedar Knob. Elevations of both sites range from 650 to 800 meters. Due to the extreme exposure to wind and water stress, trees on these sites have developed irregular crowns, often with contorted or "flag-tree" form. Older trees with such form, especially on the CKJ site, exhibit occasional heart rot.

## MATERIALS AND METHODS

We collected, mounted, and sanded increment cores and cross-sections, using standard techniques (e.g., Stokes and Smiley, 1969; Fritts, 1976). For the most part, we sampled only those trees thought to be old relative to nearby conspecifics, based on criteria including bark texture, canopy form and stem and branch morphology. However, we also cored several younger-looking trees at CKJ, specifically to ensure that we obtained clearly visible rings for the recent few decades for crossdating purposes. On the DKP site, we extracted cores from 30 pine trees; 22 *Pinus pungens*, 7 *P. virginiana*, and 1 *P. rigida*. On the CKJ site, we extracted cores from 28 living trees and 7 dead trees, and cut radial cross-sections from 3 dead and fallen trees, all *Juniperus virginiana*.

Cores were first visually crossdated under magnification with the aid of the "list method" described by Yamaguchi (1990), where marker years are listed in tabular form and compared between samples. We were also able to use a list of the normalized indices from the original Cook chronologies for comparison with our new time series prior to 1980. Individual radii were measured on a Velmex sliding-stage micrometer (0.001 mm resolution) interfaced with a computer. The crossdating quality-control program COFECHA (Holmes, 1983) was used as an independent test of our crossdating, and to assist with the detection of locally absent rings in some cores.

We standardized the correctly-dated tree-ring series and processed the raw measurements into a mean value function using the program ARSTAN (Cook and Holmes, 1986). This program employs autoregressive modeling for analyzing the effects of autocorrelation on the mean chronology indices. Both "prewhitened" (effects of autocorrelation removed) and "reddened" (containing the pooled autocorrelation common to all series) series are generated for further analyses.

For detrending our time series we used an interactive approach; each series was detrended individually, taking into account any vagaries associated with endogenous disturbance (Cook and Kairiukstis, 1990). We maintained a conservative approach by employing single detrending, fitting either a negative exponential curve or a straight line of horizontal or negative slope. Such an approach is based on the geometric constraint of adding a constant volume of wood to a cylinder of increasing circumference, which results in a classic negative exponential trend in annual radial growth in open canopy forests (Fritts, 1976). Occasionally a radius may exhibit anomalous growth departures that require the use of spline fitting, to reduce the effects of endogenous disturbance on the time series (Cook and Peters, 1987). For this study, however, it was not necessary. We used a bi-weight robust mean for calculating the mean value function, which reduces the effects of outliers on the resultant chronology indices (Cook and Kairiukstis, 1990).

We generated response functions by calculating the correlation coefficients between the ARSTAN chronologies (containing the pooled autocorrelation) and mean monthly temperature and total monthly precipitation. For this purpose we used the West Virginia regional meteorological data from 1898 to 1997, which was obtained from NOAA. We used a point by point regression technique for calculating the correlation coefficients.

## RESULTS AND DISCUSSION

Cook's original DKP chronology (Figure 1a) was based on 24 *Pinus* spp. radii and spanned the 261 years from 1717 to 1978. His 507 year CKJ chronology (Figure 2a) was based on 17 radii of *Juniperus virginiana*, and spanned from 1476 to 1983. Our updated DKP chronology (Figure 1b-c) now covers the

332 year period from 1666 to 1998 AD, and the updated CKJ chronology (Figure 2b-c) extends 522 years from 1476 to 1998. Since we successfully combined our chronologies with Cook's, these chronologies have now been updated to the most recent year. As of this writing, only the DKP series has been extended to an earlier date, due to the time constraints of the NADEF. We appear to have collected adequate subfossil material from both sites, however, for further backward extension of both time series in the near future.

Crossdating problems and time constraints limited the sample depth to 18 new samples for DKP and 8 for CKJ. We found many false, locally-absent, and "pinched-out" growth rings in *J. virginiana*, which made the crossdating for CKJ challenging. With further effort, however, most of the new samples can be worked into the chronology, including the several subfossil logs that were collected. Crossdating for the DKP *P. pungens* and the CKJ *J. virginiana* produced series intercorrelations of 0.459 and 0.611, respectively. Relevant chronology statistics are listed in Table 1.

While the inter-species differences between the DKP and CKJ chronologies is evident, there is some notable agreement between the key marker years at both locations. For example, both chronologies show marked growth reductions for years 1850, 1930, 1969, and 1977. Both also show a general period of reduced growth during the 1950s and 60s, followed by an increasing trend-in-mean coupled with an increase in variance over the most recent 2 decades. The meteorological records show that rainfall variability over this time period shows similar patterns, and this is discussed below.

*Age-class distribution*

We analysed the age-class structure at both sites (Figure 3). At DKP, the age-class distribution of *P. virginiana* shows a single cohort that became established around AD 1870. Similarly, many *P. pungens* became established at that time. A suspected drought in 1850 may have increased fire susceptibility in that year, as the dry, exposed conditions on these sites make them appear prone to fire. Thus, these young cohorts of *P. virginiana* and *P. pungens* may reflect post-fire establishment. Charcoal found on this site provides evidence for such a fire, though as of this writing it is not possible to determine the date of burning. Nor is it possible to determine if other recent fires have effected these sites, and this link to fire remains speculative.

At the CKJ site, the age-class distribution for *J. virginiana* shows continuous recruitment over many centuries. Given that this species bears serotinous cones, the continuous recruitment may reflect frequent fire. It is true, however, that *J. virginiana* cones may open during very hot summer conditions on exposed sites, even without fire (P. Brose, pers. comm.). In the absence of stand-devastating disturbance and the virtual absence of interspecific competition (few tree species can persist in this harsh environment), the recruitment of *J. virginiana* can continue without interruption for prolonged periods. It is likely that the continuous recruitment pattern we see here is more indicative of the absence of disturbance for at least the past 3 to 5 centuries, than it is a continuous regime of frequent fires.

**Climatic analysis**

Response functions analyses confirmed the earlier findings of Cook (pers. comm.), that a significant, direct relationship with rainfall is evident for both species at these sites. Analysis with our updated chronologies (Figure 4) shows significant ($P < 0.05$), direct correlations with summer precipitation, and significant, inverse correlations with summer temperature ($P < 0.05$). Additionally, there are direct correlations between tree growth and March temperature for both sites, also significant at the 0.05 level of confidence.

The opposite sign for the relationships with summer precipitation and temperature likely reflects the intercorrelation between these two variables. Cool temperature coupled with adequate moisture may lead to increased water-use efficiency (WUE) and, in turn, an increase in radial growth. An increase in rain and cloudiness also corresponds to lower maximum temperature which can reduce the chance for moisture

stress (Fritts, 1976). The positive correlation between tree growth and March temperature at both sites, implies some degree of physiological pre-conditioning for growth, possibly due to an increase in water availability from snow melt at the onset of the growing season, rather than a direct response to temperature per se. An exploration of this relationship is beyond the scope of this paper, and will not be discussed further.

Most of the significant years of below-normal growth at both sites can be explained by drought for the period of calibration. Slow growth in 1930, for example, corresponds to a severe drought in that year, which is evident in the meteorological data. In addition to drought, slow growth on these sites may be exacerbated by exposure to wind, which might increase evapotranspiration in already stressed trees.

On both sites a marked period of slow growth extended from about 1950 through 1970, most pronounced at DKP. It must be considered that this slow-growth period may be due to acid deposition, since the pronounced recovery roughly follows a strengthening of air-quality regulations. However, the changes in summer precipitation (May-July) shows very similar characteristics, and is a more likely explanation based on our response functions analysis. Therefore we conclude that there is no evidence in support of an acid rain effect in either of these two study sites.

The general growth increase from the early 1970s through 1998 corresponds to an overall increase in precipitation during that same time. However, the question that this growth increase might be driven by an increase in atmospheric carbon dioxide must be addressed. Graybill (1987) found rapid growth in high-elevation conifer stands in California that he attributed to an increase in atmospheric $CO_2$. In particular, our study sites are no doubt influenced by industries from the Ohio River Valley and the Midwest. However, Cook et al. (1996) have shown that recent growth increases in *Lagarostrobus franklinii* in Tasmania are more closely related to temperature than $CO_2$, based in part on the year-to-year tracking of tree-growth with variability in temperature. A response to $CO_2$ fertilization would be expected to result in a monotonic increase, with a dampening of the sensitivity to year to year fluctuations in climate. Indeed, in both DKP and CKJ the high-frequency response to drought is consistently strong during the recent two decades. If $CO_2$ fertilization were the driving force behind this growth increase, the trees would be expected to over-predict rainfall and this is not the case. We conclude that there is no evidence for the effects for $CO_2$ fertilization in either DKP or CKJ. Given the strong correlation found between ring width indices and summer precipitation, it appears the growth increase in recent decades is linked to an overall increase in precipitation.

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