

RESEARCH REPORT

DENDROCHRONOLOGICAL POTENTIAL OF THE ARCTIC DWARF-SHRUB *CASSIOPE TETRAGONA*

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ABSTRACT

In this report, we describe the use of dendrochronological techniques on the circumpolar, evergreen dwarf-shrub, *Cassiope tetragona*. Using techniques such as crossdating and standardization, and the software programs COFECHA and ARSTAN, we developed *C. tetragona* growth and reproduction chronologies for sites in the Canadian High Arctic. High-resolution chronologies may be used to reconstruct past climate and phase changes in large-scale modes of atmospheric circulation (e.g. Arctic Oscillation, North Atlantic Oscillation), to investigate the growth and reproductive responses of the plant to ambient and manipulated environmental variables, and to reconstruct the plant's past ecohydrology ($\delta^{18}\text{O}$, δD , $\delta^{13}\text{C}$), gas exchange ($\delta^{13}\text{C}$) and mineral nutrition ($\delta^{15}\text{N}$). As *C. tetragona* is a circumpolar species, chronologies may be developed throughout the Arctic at sites where no trees exist, and thus provide new information on the past climate and environmental history of sites and regions previously unstudied.

Key words: *Cassiope tetragona*, arctic white heather, dendroclimatology, isotopes, Arctic, Canada.

INTRODUCTION

Numerous dendrochronological studies have been conducted in the sub-arctic of Alaska and Canada (e.g. Garfinkel and Brubaker 1980; Cropper 1982; Jacoby *et al.* 1985; Payette *et al.* 1985; Jacoby and D'Arrigo 1989; Szeicz and MacDonald 1995; Tardiff *et al.* 2001), Fennoscandinavia (e.g. Briffa *et al.* 1990; Lindholm and Eronen 2000; Grudd *et al.* 2002; Helama *et al.* 2002;) and Russia (e.g. Briffa *et al.* 1995; Gervais and MacDonald 2000; Jacoby *et al.* 2000; Hantemirov and Shiyatov 2002; Naurzbaev *et al.* 2002). However, in arctic (and alpine) ecosystems, dendrochronological-based research is limited by the simple fact that there are no trees to study. Thus, the ecological and climatological history of these sites and regions is often not fully understood. Although the interpretation of other proxy data sets, including

ice core records, and freshwater diatoms, pollen and varves from lake sediment cores, has provided information on the environmental history of multiple arctic sites (e.g. Overpeck *et al.* 1997), some of the proxies are temporally and/or spatially limited. The spatial limitations of these proxies, including tree-ring records at tree-line, pose certain dilemmas when climate is reconstructed for one region and then extrapolated over much larger and geographically different areas (Jones and Kelly 1983). In addition, none of these proxies, aside from tree rings, are based directly on the terrestrial components of arctic ecosystems and provide high resolution records of past environmental conditions. These gaps in knowledge hinder efforts to understand recent climate change in the circumpolar region, its impact on arctic ecosystems, and the key role that high northern latitudes play in the global climate system. In this report, we briefly describe the use of dendrochronological techniques on a tundra shrub, *Cassiope tetragona*, and

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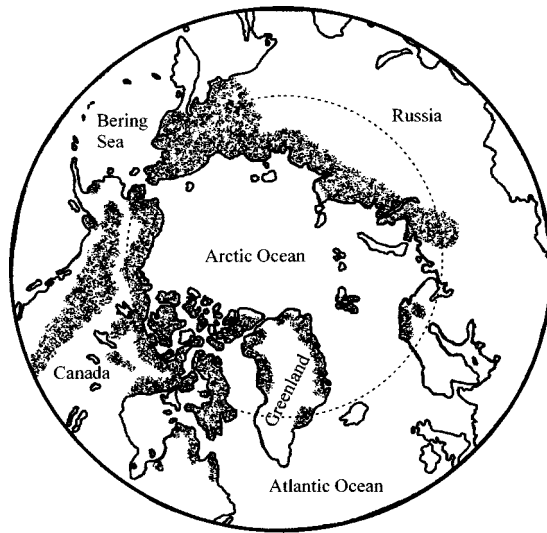


Figure 1. Map of the Arctic showing the distribution of *Cassiope tetragona* (L.) D. Don ssp. *tetragona* and *C. tetragona* (L.) D. Don ssp. *saximontana* (Small) A. E. Porsild (stippled areas). The plant's distribution is redrawn from Moss (1959), Porsild (1964), Rousseau (1974), Hultén (1968, 1971), Porsild and Cody (1980), and Cody (2000). The Arctic Circle (66° N) is shown as a dashed circle.

the current and future research directions using *C. tetragona* chronologies.

Cassiope tetragona

Cassiope tetragona (L.) D. Don (Ericaceae) (arctic white heather) is a long-lived (100+ years), evergreen, dwarf-shrub with a circumpolar distribution (Figure 1). The species is a component of, and often dominant in low shrub-heath, dwarf shrub-heath and mixed heath communities (Bliss and Matveyeva 1992). It is also found in alpine ecosystems of the northern Rocky Mountains.

The plant produces two alternating sets of opposite leaves along the stems, forming four distinct rows (Figure 2a). The leaves remain attached to the stem for 20+ years (Callaghan *et al.* 1989; Johnstone and Henry 1997). Along individual stems, wave-like patterns in leaf-lengths are apparent on most plants. Small leaves produced in the spring and fall of each year frame larger leaves formed during the summer (Warming 1908). The smaller leaves delimit an annual growth increment (AGI). Callaghan *et al.* (1989) and Havström *et al.*

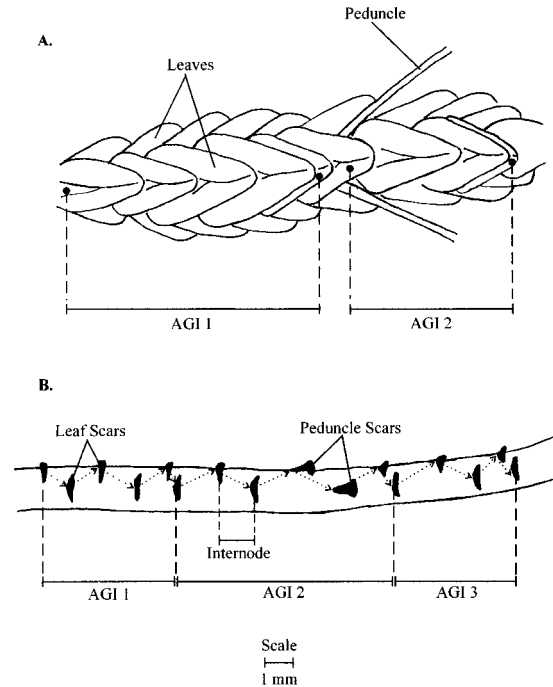


Figure 2. Schematic diagrams of *Cassiope tetragona* stems showing annual growth increments (AGI) as defined by: (a) the wave-like patterns in leaf-lengths (Callaghan *et al.* 1989), and (b) the sum of the distances between leaf node scars (internodes) (Johnstone and Henry 1997). Following removal of two adjacent rows of leaves (b), the arrows indicate the direction of measurement with the terminus of each year's growth delimited by the shortest internode length at the end of each wave series. For simplicity, only two rows of leaf node scars are shown in (b).

(1993,1995) measured individual leaf-lengths (to 0.1 mm) to identify and date individual AGIs, and to develop chronologies up to 26 years in length.

Johnstone and Henry (1997) determined that the distances between leaf node scars in adjacent leaf rows showed a similar intra-annual, wave-like pattern when compared with the leaf-lengths (Figure 2b). Annual growth increments are measured as the sum of the internode lengths with the terminus of each year's growth delimited by the shortest internode length at the end of each wave-series (Johnstone 1995). As the leaf node scars remain visible along the length of the stem for long periods, Johnstone and Henry (1997) used the pattern to measure (to 0.01 mm) and date AGIs and to develop longer chronologies (35 years). Johnstone and Henry (1997) also generated chronolo-

Table 1. Selected ARSTAN (Cook 1985) results for the Hot Weather Creek growth (AGI, Leaf) and reproduction (Bud, Peduncle) chronologies. Chronologies cover a common time interval selected by the software program ARSTAN to maximize the number of stems included in the calculations. The common intervals are shorter than those shown in Figure 4. AGI = Annual Growth Increment; Leaf = number of leaves produced per year; Bud = number of flower buds produced per year; Peduncle = number of flower peduncles produced per year.

	AGI	Leaf	Bud	Peduncle
Common Interval	1967–1997	1969–1997	1974–1997	1973–1997
# of Plants	11	11	11	11
# of Stems	25	26	24	20
\bar{r}_{br}	0.07	0.04	0.02	0.02
$1 - \bar{r}_{wr}$	0.90	0.92	0.98	0.92

\bar{r}_{br} is the between-plant signal.

$1 - \bar{r}_{wr}$ is the within-plant noise.

gies for the annual production of leaves and flowers. Recently, we constructed AGI chronologies of 113–118 years in length, as well as chronologies for the annual production of leaves, flower buds and flowers from high arctic sites in Canada (Rayback and Henry in press).

USING DENDROCHRONOLOGICAL TECHNIQUES ON *CASSIOPE TETRAGONA*

Below, we highlight some of the interesting parallels with and divergences from tree-ring-based research and recent developments in the use of dendrochronological techniques on *C. tetragona*. Complete descriptions of the dendrochronological techniques used and principles applied to *C. tetragona* in fieldwork, lab work and the construction of chronologies are available in Johnstone and Henry (1997) and Rayback (2003).

Crossdating

Crossdating ensures the proper placement in time of individual AGIs by matching common patterns of annual growth (Fritts 1976). We crossdated *C. tetragona* stems through visual comparisons of the measurement series (Stokes and Smiley 1968), and by statistically comparing the measured segments with the full chronology (COFECHA, Dendrochronology Program Library described in Holmes *et al.* (1986)). Aside from Johnstone and Henry (1997), crossdating of *C. tetragona* chronologies was not carried out in previous studies

(Callaghan *et al.* 1989; Havström *et al.* 1993, 1995; Welker *et al.* 1995; Aanes *et al.* 2002).

The use of skeleton plots, a process of graphically representing the AGI variations in each stem, proved to be the most effective method of crossdating live *C. tetragona* stems within and between plants (Figure 3). Measurement accuracy and crossdating errors were also detected through the use of COFECHA (Holmes *et al.* 1986). However, given high levels of intra- and inter-plant variability and the short length of some stems (20–30 years), using COFECHA efficiently was challenging.

We believe the high level of intra-plant variability in *C. tetragona* chronologies, as indicated by the ARSTAN statistics for the Hot Weather Creek, Ellesmere Island site (79°58'N, 84°28'W), is the product of plant architecture and associated microenvironmental conditions, as well as within-plant resource partitioning (Table 1) (Cook 1985; Havström *et al.* 1993; Johnstone and Henry 1997). The position of individual stems within a densely branching plant may influence the amount of solar radiation each plant part receives, as well as surface temperature. Resource partitioning (*e.g.* water, nutrients, photosynthates) among stems could influence the constancy of annual growth and reproduction and thus, modify the plant's response to environmental conditions. In addition, inter-plant variability may result from poorly understood community dynamics (*e.g.* competition) within arctic ecosystems (Johnstone and Henry 1997; Rayback 2003). Further work in chronology de-

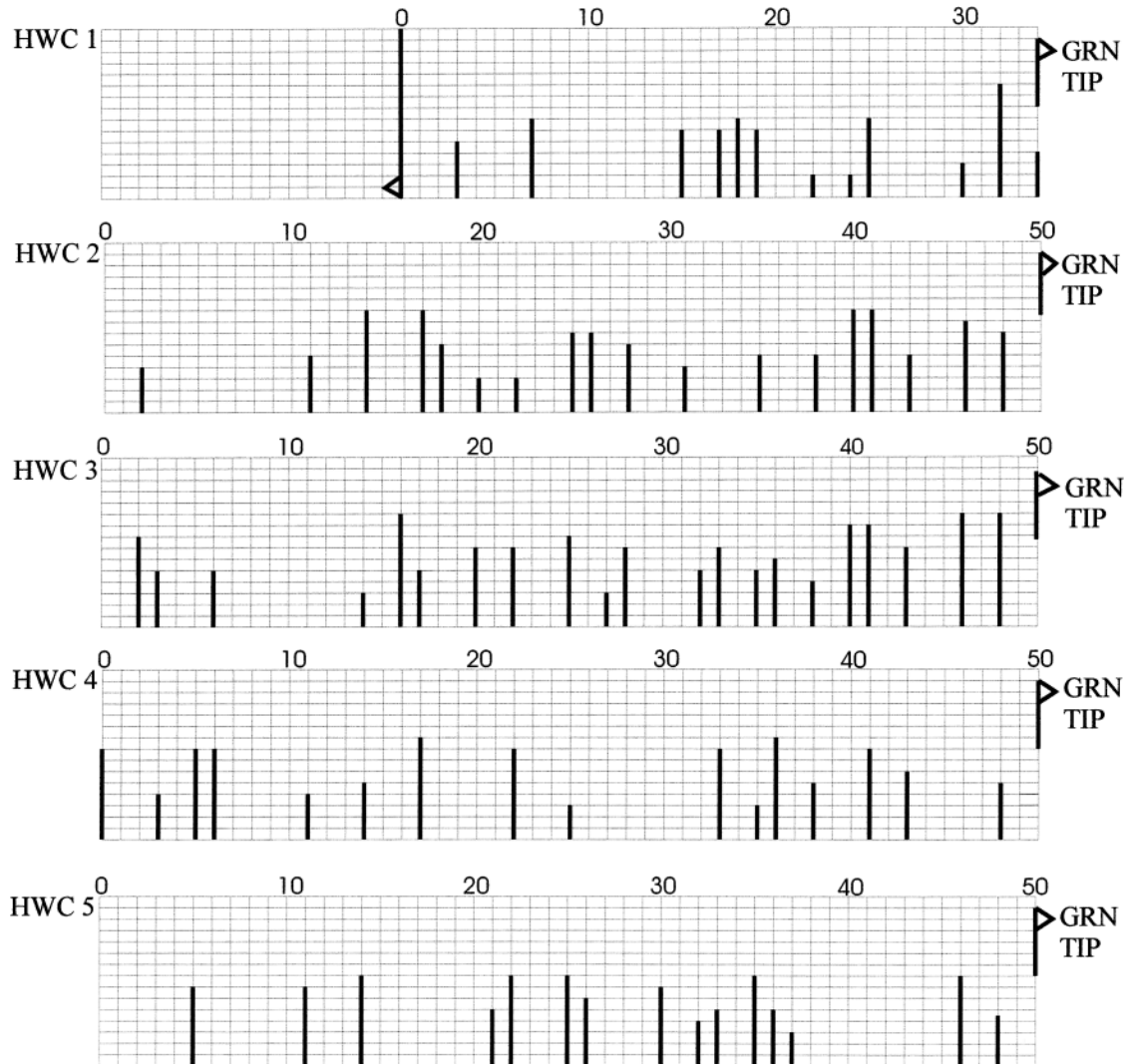


Figure 3. Example of skeleton plots of one stem from each of five individual *Cassiope tetragona* plants sampled at Hot Weather Creek (HWC), Ellesmere Island, Canada. GRN TIP = live green leaves and leaf bud at stem tip.

velopment is underway to better understand and to reduce the amount of intra- and inter-plant variability in order to increase confidence in annual date assignment. For example, the selection and measurement of one dominant stem per plant may serve to increase the common signal in the master chronology.

Standardization

The purpose of standardization is to remove non-climatic growth trends from the AGI series to

allow the resultant standardized values of individual plants to be averaged together into a master chronology (Cook and Kairiukstis 1990). Similar to many tree-ring measurement series, variation in the length of the AGIs is caused by longer-term trends that are not related to climatic fluctuations, such as the uneven growth of the species over its lifetime (Fritts 1976; Cook and Kairiukstis 1990). We observed smaller AGIs in the first years of shoot growth on *C. tetragona* stems sampled from high arctic sites. In addition, we hypothesized juvenile growth effects influence reproduction in *C.*

tetragona (Johnstone and Henry 1997). However, as no one has determined the year of plant establishment with certainty, we estimate that *C. tetragona* reproduces after *ca.* 10–15 years of age. To minimize juvenile effects, all chronologies are standardized. As well, flower bud and flower chronologies are truncated to begin at the first year of visible bud formation or flower production.

As in dendrochronological applications, we generated standardized *C. tetragona* growth and reproduction chronologies from raw measurements using the software program ARSTAN (Cook 1985). No other study of *C. tetragona* has used ARSTAN to standardize chronologies. In the Hot Weather Creek study, we selected flexible cubic splines to standardize the *C. tetragona* chronologies (Figure 4).

The low-pass filters smooth out local fluctuations that constitute the high-frequency variation in order to produce smoothed estimates of the actual series (Cook and Peter 1981). We determined that smoothing splines were necessary to maximize the inter-shoot correlation without losing the climate signal entirely. Small changes within the plant architecture because of inter-shoot shading, resource partitioning or apical dominance would likely have as great an effect on individual stem growth, leaf production and reproductive development as climate over the lifetime of the plant (Johnstone 1995; Rayback 2003). Thus, intra-plant effects had to be filtered as much as possible.

Based upon the signal-to-noise ratio (SNR) (Wigley *et al.* 1984; Cook and Kairiukstis 1990), we selected cubic-splines on the order of 40–60 years to standardize the individual series. Although the SNRs for the Hot Weather Creek chronologies were low (*e.g.* AGI SNR = 0.63), an indication of the high amount of noise present in the chronologies, no other standardization method yielded higher SNR values. One notable drawback to standardizing measurement series with a flexible cubic spline is that the ability to reconstruct climate trends that last multiple decades to centuries is limited (Cook and Kairiukstis 1990). However, the length of most live *C. tetragona* chronologies (*ca.* 100 years or less) essentially obviates this concern.

CURRENT AND FUTURE RESEARCH DIRECTIONS

Climate Reconstruction

Using *C. tetragona* chronologies, past climate may be reconstructed for sites across the circum-polar north where trees are absent and where climate stations are few. Recently, we reconstructed average summer air temperature for Alexandra Fiord, Ellesmere Island (78°53'N, 75°55'W) (1895–1994) (Rayback and Henry in press), and for central Ellesmere Island (*ca.* 79° N), Canada (1948–1994) (Figure 5; Table 2). The central Ellesmere Island model explained 51% of the climatic variance (R^2 adj, adjusted for loss of degrees of freedom) and passed standard dendrochronological calibration and verification tests (Table 3). We believe it is possible to extend the length of the time series by crossdating subfossil stems into the live chronologies, although this has yet to be attempted. *Cassiope tetragona*-based climate reconstructions may also be used in conjunction with other arctic proxy data (*e.g.* tree rings, ice cores, lake varves, freshwater diatoms), where available, to reconstruct the paleoclimatological and paleoecological histories of northern sites (Rayback and Henry in press). The air temperature trend shown in the central Ellesmere Island model (1948–1994) corresponds well with an arctic-wide, multiproxy record of summer air temperature (Figure 6) (Overpeck *et al.* 1997).

Growth/Reproduction–Climate Relationships

Retrospective analysis of *C. tetragona* chronologies has been used to investigate the past growth and reproduction responses of *C. tetragona* populations across time and/or space to experimental and/or ambient environmental conditions (Callaghan *et al.* 1989; Havström *et al.* 1993; Michelsen *et al.* 1996; Molau 2001). In association with the International Tundra Experiment (ITEX), we used retrospective analysis of *C. tetragona* chronologies for plants sampled in treatment and control plots to investigate the growth and reproductive responses both prior to (1986–1991) and during (1992–1998) experimental warming (Rayback 2003). In our study, *C. tetragona* reproduction re-

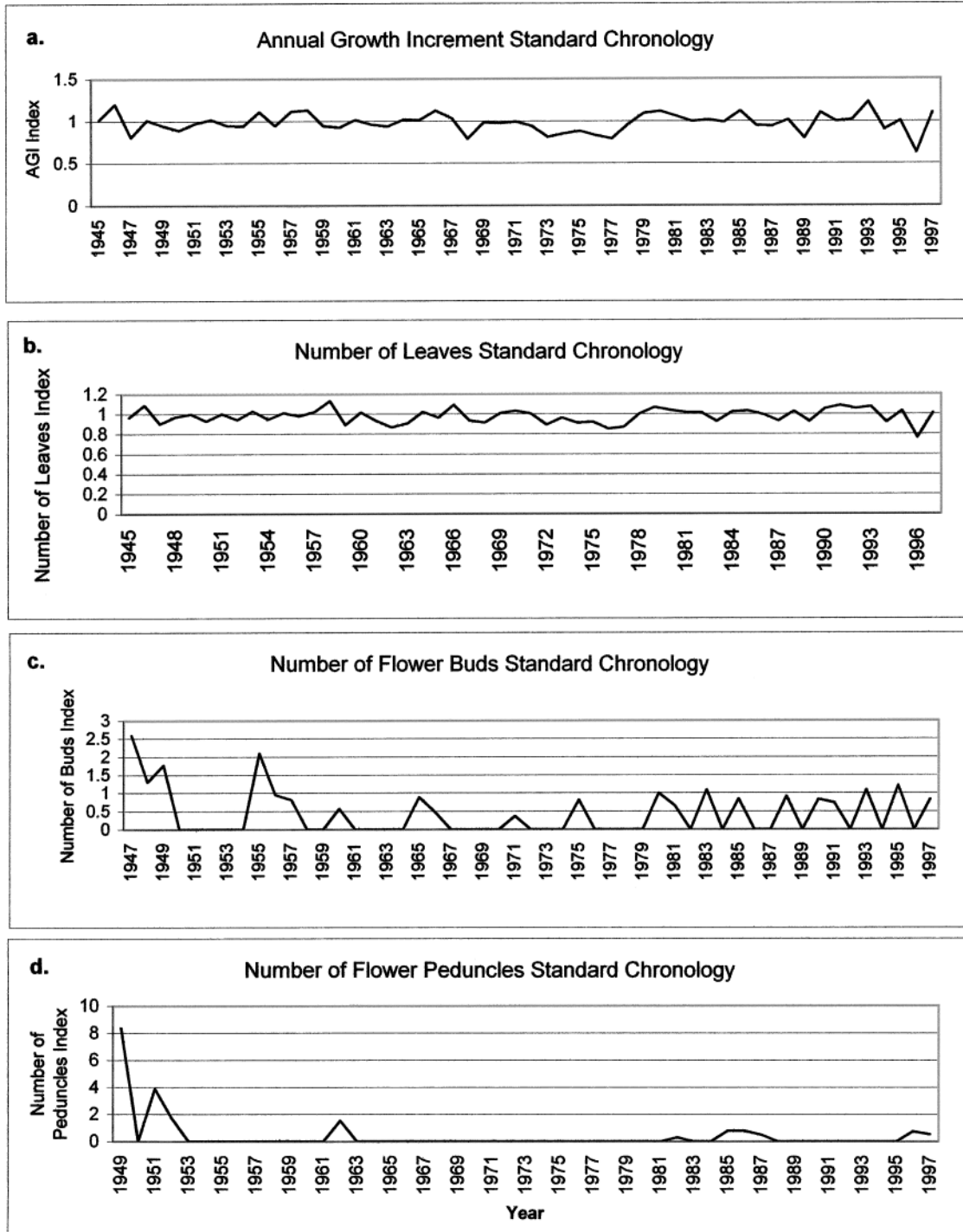


Figure 4. Standardized chronologies for (a) annual growth increments (AGI), (b) annual production of leaves, (c) annual production of flower buds, and (d) annual production of flower peduncles for Hot Weather Creek, Ellesmere Island, Canada.

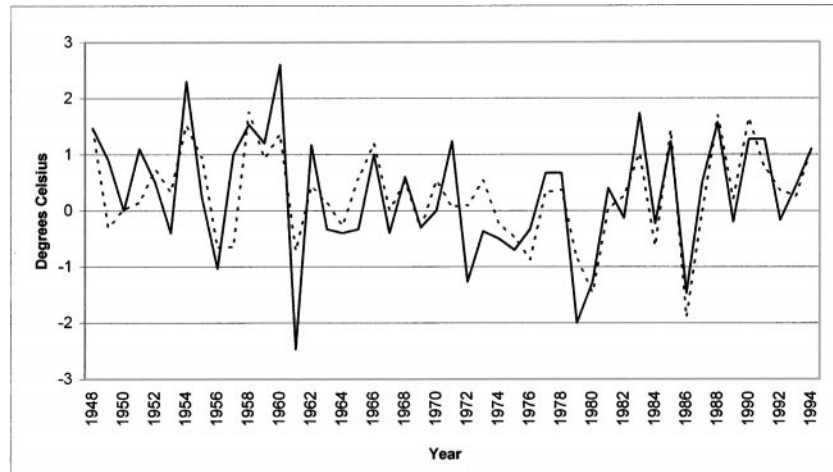


Figure 5. Comparison of July–September average air temperature data from the Eureka High Arctic Weather Station, Ellesmere Island (solid line) with the reconstructed model for central Ellesmere Island (dashed line) from 1948–1994.

sponded positively ($p < 0.05$) to an increase in summer growing season temperature over seven years (1992–1998), while vegetative growth remained stable.

Research linking past *C. tetragona* growth with

Table 2. Transfer function details for the July–September average air temperature model for central Ellesmere Island based on chronologies from Alexandra Fiord and Hot Weather Creek, Ellesmere Island.

Predictor Variables	Full Model 1948–1994	Early	Late
		Calibration 1948–1980	Calibration 1964–1994
Constant	−19.751**	−9.536*	−18.574**
LowLea3	9.907*		7.554*
LowBud2	−1.171*	−1.206*	
BenAGI	8.777	8.397*	8.874**
BenBud2	0.68*		0.503
BenBud3	−0.868*	−0.007	−1.174**
HWCAGI3	−2.973*	−4.385*	−2.845*
HWCLea	5.354*	7.139*	5.655*

* $p < 0.05$, ** $p < 0.01$.

Low = Lowland site at Alexandra Fiord

Ben = Bench site at Alexandra Fiord

HWC = Hot Weather Creek site

AGI = annual growth increment for year t

AGI3 = annual growth increment for year $t - 1$

Lea = number of leaves for year t

Leaf3 = number of leaves for year $t - 1$

Bud2 = number of flower buds for year $t + 2$

Bud3 = number of flower buds for year $t - 1$

large-scale modes of atmospheric circulation (*e.g.* Arctic Oscillation (AO)) has provided information on site-based, plant population responses to dominant modes of past climate and clues to trophic interactions (Aanes *et al.* 2002; Welker *et al.* in press). For example, *C. tetragona* growth chronologies from Alexandra Fiord, Ellesmere Island were positively correlated with average air temperature (June–August) ($p < 0.05$), and negatively correlated with total monthly precipitation (June–August) and the summer Arctic Oscillation (AOS) index (1948–1996) ($p < 0.05$) (Table 4a). We calculated the AOS index by averaging the monthly AO index values from June–September (<http://tao.atmos.washington.edu/data/ao>). High AOS index values were negatively correlated with average air temperature (June–August) ($p < 0.05$) and positively correlated with total monthly precipitation (June–August) ($p < 0.01$) during the growing season (Table 4b). When the Arctic Oscillation is in the positive phase (high index values), low pressure is centered over the Arctic (Thompson and Wallace 1998). During the summer months, lower-than-average sea level pressure is associated with increased cyclonic activity and cloudier, wetter conditions (Serreze *et al.* 1997; Aanes *et al.* 2002). Thus, high AOS index values may be associated with unfavorable growing season conditions (*e.g.* lower radiation influx) and result in the decreased

Table 3. Calibration and verification statistics for the central Ellesmere Island average air temperature reconstruction.

Calibration						Verification					
Model	Period	n	R	R ²	R ² adj	Model	Period	n	r	RE	CE
Early	1948–1978	31	0.65	0.42	0.30	Late	1979–1994	16	0.67**	0.30	0.29
Late	1965–1994	30	0.81	0.65	0.56	Early	1948–1964	17	0.53*	0.16	0.06
Full	1948–1994	47	0.76	0.58	0.51						

* = $p < 0.06$; ** = $p < 0.01$.

n = sample size

R = multiple correlation coefficient

R² = multiple coefficient of determination

R²adj = multiple coefficient of determination adjusted for loss of degrees of freedom

r = correlation coefficient

RE = reduction of error statistic

CE = coefficient of efficiency

growth of *C. tetragona* (Table 4a) (Welker *et al.* in press).

Isotopic Analysis

Finally, long-term, annually-resolved, isotopic time series may be reconstructed from *C. tetragona* chronologies and used to investigate the past

ecohydrology ($\delta^{18}\text{O}$, δD , $\delta^{13}\text{C}$), gas exchange ($\delta^{13}\text{C}$), and mineral nutrition ($\delta^{15}\text{N}$) in *C. tetragona* plants under experimental (*e.g.* experimental warming, fertilization, snow manipulation) and ambient conditions. Welker *et al.* (1995) investigated a *C. tetragona*-based, isotopic time series from Svalbard, Norway (79°N, 13°E) and found that winter climate conditions indirectly influenced

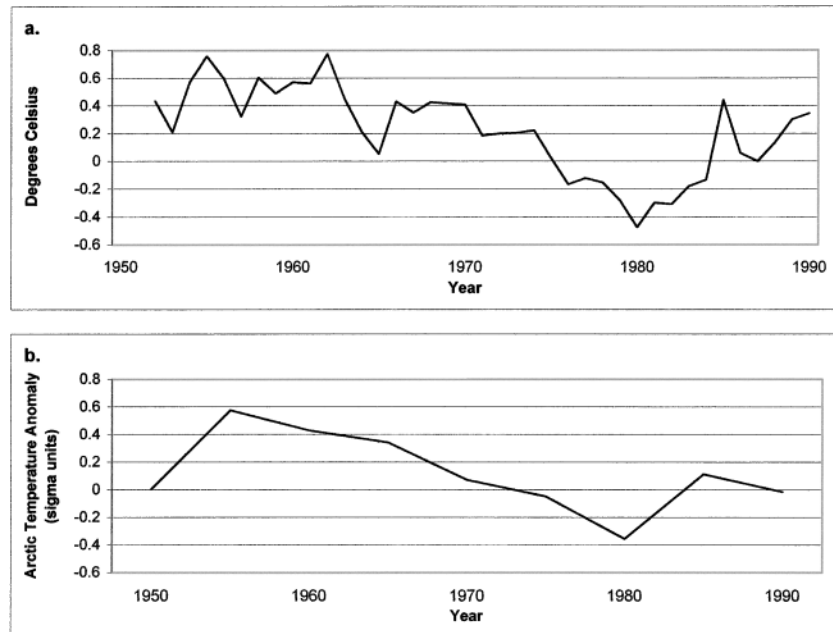


Figure 6. Comparison of the (a) standardized reconstruction of July–September average air temperature departures for Central Ellesmere Island smoothed with a five-year running mean, and the (b) standardized, arctic-wide, average summer air temperature time series plotted as sigma units (Overpeck *et al.* 1997) for the period, 1950–1990. Data in Figure 6b are archived at the World Data Center for Paleoclimatology, Boulder, CO, USA (www.ncdc.noaa.gov/paleo/recons.html).

Table 4. Pearson's product-moment correlation coefficients relating: (a) growth (AGI, Leaf) chronologies from Alexandra Fiord, Ellesmere Island with June–August average air temperature (T) and total precipitation (P) data measured at the Eureka High Arctic Weather Station, Ellesmere Island (1948–1996), and with the summer Arctic Oscillation (AOS) index; (b) AOS index with June–August average air temperature (T) and total precipitation (P) from the Eureka High Arctic Weather Station (1948–1996). AGI = Annual Growth Increment; Leaf = number of leaves produced per year.

a.	AGI	Leaf	b.	AOS
June–August T	0.34*	0.31*	June–August T	–0.31*
June–August P	–0.14	–0.15	June–August P	0.47**
AOS	–0.32*	–0.25		

* = $p < 0.05$; ** = $p < 0.01$.

the plant's physiological performance, including gas exchange ($\delta^{13}\text{C}$) and plant water relations (δD), in the summer. Recently, we reconstructed 20th Century phase changes in the AO based on a *C. tetragona* isotopic record from Alexandra Fiord, Ellesmere Island, Canada (Welker *et al.* in press). Low $\delta^{18}\text{O}$ values recorded in the chronology from 1935–1970 preceded a gradual enrichment around 1970, and later, an abrupt upward shift in the $\delta^{18}\text{O}$ values in 1990. Enriched $\delta^{18}\text{O}$ values present in organic matter indicate high levels of rain water in the soil and an increase in the use of rain water in plant metabolism. In contrast, lower $\delta^{18}\text{O}$ values in organic matter indicate higher levels of snow melt water in soils and the use of snow melt water by plants (Welker 2000; Dawson *et al.* 2002; Welker *et al.* in press). In addition, we found a positive correlation between the AO and $\delta^{18}\text{O}$ values ($p < 0.05$), indicating that during the recent positive phase (1970–1996) of the AO when the $\delta^{18}\text{O}$ values were enriched, soil and plant waters were dominated by rain water during the growing season (Welker *et al.* in press). The enrichment in $\delta^{18}\text{O}$ values coincides with increased summer precipitation associated with greater cyclonic activity, higher spring surface air temperatures, lower sea level pressure, and the intensification of the AO in the Arctic during this period (Walsh *et al.* 1996; Serreze *et al.* 2000; Thompson *et al.* 2000; Welker *et al.* in press). Clearly, future work using dendrochronological techniques on *C. tetragona* plants from sites across the circumpolar north holds great promise, and offers new research directions for investigating the past climatic and environmental history of arctic (and alpine) sites beyond treeline.

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