RADIAL GROWTH OF OAK AND ASPEN NEAR A COAL-FIRED STATION, MANITOBA, CANADA

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ABSTRACT

Eighteen stands of bur oak (*Quercus macrocarpa* Michx.) and trembling aspen (*Populus tremuloides* Michx.) were sampled and analyzed using dendrochronological methods to study the potential effects on tree growth of emissions from a 132 MW coal-fired generating station. Sixteen stands were sampled within a 16-km radius of the station, and two control stands were sampled outside of the range of influence, at distances > 40 km. All stands showed similar radial growth patterns from 1960–2001, regardless of distance from or direction relative to the generating station, and a number of stands, including the controls, had below average growth after 1970. Both species were significantly affected by climatic factors, showing decreased radial growth with increasing June temperature. The species differed in their growth responses to spring precipitation and temperature in the previous October. One bur oak site displayed marked radial growth decline beginning in the mid-1970s, strongly pronounced following 1977. This decline does not appear to be related to emissions from the station, but is suspected to be a result of poor site conditions (shallow soil developed over calcareous till), confounded by a change in drainage (a road was built adjacent to the stand in 1977, perpendicular to the direction of drainage). The below average growth seen in 1970–2001 across most stands is likely attributable to stand dynamics and age effects.

Keywords: *Quercus macrocarpa*, *Populus tremuloides*, coal-fired generating station, sulphur dioxide, dendrochronology.

INTRODUCTION

The growth of trees is largely a function of environmental conditions. Air pollutants such as sulphur dioxide and heavy metals have long been recognized as factors that influence tree growth and forest health (McClenahan and Dochinger 1985; Fox *et al.* 1986; Sutherland and Martin 1990). These pollutants can cause an inhibition of photosynthesis (Keller 1980; Malhotra and Blaue 1980), which can have a lasting effect on growth for several years (Fritts 1976). Growth reduction can be manifested in many parts of the tree, particularly in radial growth. More specifically, reduced photosynthesis slows cambial activity and

consequently wood production (Yunus and Iqbal 1996). Obtaining long-term records of tree growth is desirable in many air pollution studies, and tree rings are a readily available source of baseline information on forest growth and productivity that can predate present instances of increased air pollution (Cook and Innes 1989).

Because tree rings integrate many environmental influences, a weak pollution signal may be embedded in a high level of natural environmental noise (Cook and Innes 1989). Therefore, the roles of natural determinants of tree growth, particularly climatic factors, must be evaluated critically before a clear interpretation of air pollution effects on tree growth can be made (LeBlanc *et al.* 1987). It is assumed that all trees respond to climatic conditions to varying degrees, and sites that are influenced by non-climatic factors are expected to pro-

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duce ring-width patterns different from those seen in sites that are limited only by climate (Thompson 1981). By comparing the climatic response of trees from different sites in a region, it is possible to determine whether other environmental factors exist, such as air pollution, which affect radial growth. This may be particularly useful when examining the effect of point source pollution on radial growth patterns, especially when historical emission records are available.

It is also important to recognize that sensitivity to different environmental factors varies from species to species. This applies to both natural and human-induced stress factors, and therefore surveys of single species may not allow generally valid conclusions in forest health studies (Schweingruber 1985). The use of two or more species is important in these types of investigations, to accurately identify or rule out potential stress factors. Each individual tree and each tree species has certain ecological requirements, and because the combined effect of the site factors (*e.g.* soil conditions, stand dynamics) is integrated into the tree-ring pattern, serious consideration must be given to overall site placement (Schweingruber *et al.* 1990).

This study examines the radial growth of bur oak (*Quercus macrocarpa* Michx.) and trembling aspen (*Populus tremuloides* Michx.) trees in stands near a 132 MW coal-fired generating station. The station was commissioned in 1960 and began operation in 1961. Until 2002 (at which time, a conversion to natural gas operation was completed), operations consisted of two electrical generators, each with a 66 MW capacity. Lignite coal (0.6% sulphur, 8.7% ash content) was used to power the plant until 1993; subsequently sub-bituminous coal was utilized (0.36% sulphur, 4.25% ash content) (SENES 2001). Before flue gas exited the 76-m stack, it was directed through a multi-clone dust collector, capable of removing approximately 70% of the fly ash. The station was never equipped with electrostatic precipitators, nor did it have sulphur dioxide scrubbers. The primary operating roles were during periods of increased demand (*e.g.* winter), drought, system failure of the provincial hydro-based network, or to allow hydraulic facilities to maintain or increase reservoir storage (SENES 2001). Historically, peak years of output

were 1976–1977, 1987–1988, 1998 and 2000. Increased production in 1998 and 2000 is of particular concern in this study, as visible decline symptoms in bur oak and trembling aspen were noted by residents in the vicinity of the station in the spring of 2000. Decline included top dieback, leaf chlorosis, and whole tree mortality.

In southern Manitoba, bur oak is near its northwestern limit of distribution in North America. This species can tolerate a wide range of soil conditions and moisture levels. It grows slowly on dry uplands and sandy plains but is also found on fertile limestone soils and moist bottomlands with other hardwoods (Johnson 1990). Bur oak is considered to be a hardy species that is relatively tolerant to sulphur dioxide and nitrogen oxides as air pollutants (Taylor *et al.* 1986). Trembling aspen grows throughout the forested regions of Canada, and often occurs in mixed stands with bur oak in the study region. It is a pioneer species, and commonly colonizes recently disturbed areas. This fast-growing species is short-lived and it grows on many soil types, especially sandy and gravelly slopes (Perala 1990). Aspen species have been shown to have an intermediate sensitivity to sulphur dioxide pollution (Taylor *et al.* 1986).

The objective of this study was to determine if airborne emissions from the generating station could be linked to any forest decline noted by residents in its vicinity. To do so, both the climatic and non-climatic variations in radial growth were analyzed in stands dominated by bur oak, trembling aspen, and in mixed stands dominated by the two species.

METHODS

Study Area

The study area is approximately 60 km north of Winnipeg, Manitoba, centered on the generating station (50°08'N 96°51'W) (Figure 1). The study area had a 16-km radius (rationale explained below) and encompassed a circular area of 804 km². The area lies within the Aspen Parkland vegetation zone, and is highly modified by agriculture (Zoladeski *et al.* 1995). Forest stands situated within this agro-forestry interface are discontinuous, and the majority of these are privately owned rem-

Figure 1. Location of the study area in southern Manitoba (inset). The 16 stands selected within the study area are presented in relation to the coal-fired generating station (the two control stands, not shown, are located 42 km NW and 65 km SE of generating station).

Table 1. Location of sites relative to the generating station, with dominant tree species.

Site*	Direction	Distance (km)
N1O	North	2.3
N2O, A	North	6.1
N3A	North	8.1
N4A	North	12.7
E1O, A	East	3.9
E2A	East	5.9
E3O, A	East	8.8
E4O	East	12.6
S1O	South	7.0
S2A	South	9.2
S3O	South	10.5
S4O, A	South	12.7
S5A	South	15.3
W1O	West	5.9
W2O	West	10.6
W3O	West	14.7
C1A	Northwest	42.0
C2O	Southeast	65.0

*O indicates dominant oak representation. A indicates dominant aspen representation. Sites with both O and A indicate a mixture of the two species.

nants. The topography and geology of the study area are relatively homogeneous and soils are dominantly Chernozemic. The study area lies in the Manitoba Lowlands, once occupied by glacial Lake Agassiz, and the underlying bedrock is limestone.

The climate of the area is subhumid, cool continental, characterized by high summer and low winter temperatures (Michalyna *et al.* 1975). For the years 1971–2000, mean annual temperature was 2.6°C and mean total annual precipitation was 513.7 mm, with over 80% of the precipitation occurring as rainfall during the growing season (Environment Canada 2002). Winds at the generating station are predominantly from the south-southeast and the north-northwest, and deposition models have been produced that show maximum particulate deposition within 12 km from the station (SE-NES 2001). These models have been verified by trace element concentration in lichens within the study area (Ehnes 2002). Dust deposition contours created from lichen tissue concentrations closely shadowed the predicted south-southeast to north-northwest pattern of average annual suspended particulate matter deposition. Additionally, depo-

sition of airborne trace elements and SO₂ from industrial sources has been shown to be highest between 5 and 15 km from the point of emission (Wangen and Williams 1978; Van Voris *et al.* 1985; Bourque and Arp 1994).

Site Selection

Using digital forest inventory maps, forest stands were identified that had either bur oak or trembling aspen as the dominant tree species within a 16-km radius of the generating station. From this initial phase, stands that covered more than 2 hectares, had a crown closure > 50% (*i.e.* mature stands), and had equivalent moisture regimes were marked. To compare tree growth in different directions and at varying distances from the generating station, marked stands were selected that were north, east, south, and west of the station, at increasing distances. Along each of these four directional transects, three to five stands were chosen. In total, sixteen bur oak, trembling aspen, or mixed stands dominated by the two species within the study area were selected for dendrochronological sampling (Figure 1 and Table 1).

Additionally, two control stands were chosen that were out of the maximum range of influence of the generating station, as determined from deposition models for the generating station (SENEs 2001). The oak control stand was located 65 km SE of the station and the aspen control stand was located 42 km NW of the station.

Dendrochronological Sampling and Processing

In each of the 16 study stands and two control stands, two cores were collected at approximately 1.3 m above ground level from 10 dominant or co-dominant trees, using an increment borer. Trees with double stems, or that were immediately adjacent to another mature tree were not selected for sampling, to avoid competition effects on growth. Cross-sections were collected from 1–2 trees in some sites at approximately 1.3 m above ground level to supplement core samples. All samples were air-dried and prepared according to standard methods (Stokes and Smiley 1968). Cores and cross-sections were sanded, and all samples were visually crossdated both within trees and within each site to ensure accurate dating. Radial growth was measured to 0.01 mm precision using a Velmex measuring system. To ensure the accuracy of crossdating and measuring, the COFECHA program was utilized (Holmes 1983).

Two standardization approaches were followed. In the first, each measurement series was standardized using a horizontal straight line through the mean (bi-weight robust mean) using the ARSTAN program (Cook and Holmes 1999). This resulted in dimensionless ring-width indices for each series, which were averaged for trees within a site to produce standard site chronologies. As no de-trending method was applied to the measurement series, the standardized chronologies contained both low-frequency (*i.e.* decadal) and high-frequency (*i.e.* annual) variance.

The effect of pollutant levels on the photosynthetic capacity of trees may induce a low-frequency growth response of a decade or more in length (McClenahan and Dochinger 1985). It is therefore desirable to separate the low-frequency variation, which includes age trends as well as any long-term effects of air pollution, from the high-

frequency component variation, which includes responses to variations in climate factors as well as to short-term increases in air pollution from the generating station. A second standardization approach was carried out to separate the variance into these components. To do so, a 20-year smoothing spline was applied to all measurement series using the ARSTAN program (Cook and Holmes 1999), resulting in ring-width indices (representing the high-frequency variance) and spline curves (representing the low-frequency variance) for each site. Before averaging, the 20-year spline curves were transformed using a horizontal straight line through the mean (bi-weight robust mean). Autoregressive modeling was carried out on the high-frequency series (resulting from the 20-year spline) to remove temporal autocorrelation and to ensure independent observations, a requirement for most statistical analyses (Legendre and Legendre 1998). This resulted in residual, high-frequency chronologies for each site. For standard high-frequency chronologies in which autocorrelation was not significant ($p > 0.05$), the standard chronology was used rather than the residual chronology in subsequent data analyses.

Data Analyses

To compare historical variation in radial growth among all sites, chronology statistics for both tree species were produced using the ARSTAN program (Cook and Holmes 1999), with a common interval analysis of 41 years (covering the period of generating station operation) for bur oak and 31 years for trembling aspen (aspen chronologies were shorter in length). Sites that were sampled for oak are appended with 'O' and those that were sampled for aspen are appended with 'A'. To assess if yearly production levels of the generating station were related to radial growth, Spearman's correlations were run on yearly production (GWh) from the generating station and the three different ring-width indices (straight line through the mean, high-frequency, and low-frequency). Spearman's correlation was used here instead of parametric correlation as the yearly production values were not normally distributed. To ensure that growth in the control site was related

to growth in study sites prior to the operation of the generating station, residual chronologies (straight line through the mean) of bur oak study sites and the bur oak control site (for the period of 1920–1960) were compared using Pearson's correlations. The tree-ring records for trembling aspen did not date far enough back to allow for such a comparison.

Principal component analysis (PCA) was performed using CANOCO 4.0 (ter Braak and Smlauer 1998) on the high-frequency site chronologies (derived from the 20-year spline) to analyze the common variance among sites (18 sites and 39 years). PCA was run on both tree species (all sites); each year was treated as an object in this analysis, and each site as a descriptor (Legendre and Legendre 1998). To determine how much of the variation in radial growth was attributable to climate variables, correlation analysis was employed using PRECON (version 5.16) (Fritts *et al.* 1991). Year scores from the first and second PCA axes were correlated with meteorological data from the Winnipeg International Airport (located 35 km southwest of the generating station: 49°54'N, 97°14'W), including mean monthly temperature and total monthly precipitation (Meteorological Service of Canada 2002). The period of 1961–1999 was used in the correlation analysis as this period corresponds with operation of the generating station, the span of climatic data (available records end in 1999), and the short length of the trembling aspen chronologies. Sixteen months were used in the climate analysis, beginning with May of the previous growing season and ending with August of the current growing season.

RESULTS

Comparison of Radial Growth

Bur Oak

Chronology statistics for bur oak were similar across all sites (Table 2). Mean ring width ranged from 0.69–1.43 mm across all sites. Site N2O demonstrated the largest mean ring width, likely related to the young age of this stand relative to other bur oak stands. Mean ring width, mean sensitivity, and standard deviation for the common pe-

Table 2. Statistics for all bur oak standard chronologies resulting from detrending with a 20-year spline and for the common interval analysis.

Site	N1O	N2O	E1O	E3O	E4O	S1O	S3O	S4O	W1O	W2O	W3O	C2O
Chronology length	1916–2001	1937–2001	1919–2001	1914–2001	1923–2001	1892–2001	1906–2001	1892–2001	1897–2001	1893–2001	1897–2001	1892–2001
No. of trees	11	10	11	10	10	10	11	10	11	11	10	11
No. of radii	21	20	21	20	20	20	22	20	21	22	20	21
Mean ring width (mm)	1.14	1.43	1.13	1.20	1.06	0.92	0.69	1.01	1.36	1.05	1.31	0.95
Mean sensitivity	0.17	0.15	0.18	0.2	0.18	0.16	0.14	0.17	0.19	0.19	0.20	0.22
Standard deviation	0.16	0.15	0.19	0.2	0.21	0.17	0.15	0.19	0.22	0.16	0.18	0.2
First-order autocorrelation	0.06	0.24	0.27	0.31	0.33	0.23	0.35	0.30	0.43	0.04	0.05	0.11
Common Interval Analysis (1960–2000)												
No. of trees	11	10	11	10	10	10	11	10	10	11	10	11
No. of radii	18	20	21	19	19	19	19	20	18	22	18	21
Variance in PC1 (%)	63.87	48.32	68.20	60.8	65.11	51.24	35.31	64.51	60.03	57.82	50.36	62.85
Inter-series correlation	0.61	0.43	0.66	0.58	0.62	0.47	0.3	0.62	0.57	0.55	0.47	0.6
Mean sensitivity	0.15	0.12	0.15	0.19	0.15	0.15	0.12	0.18	0.19	0.19	0.17	0.20

Figure 2. (A) Standard chronologies for the *Q. macrocarpa* sites, standardized with a straight line through the mean. (B) High-frequency variance (standard chronology, resulting from a 20-year smoothing spline) for all *Q. macrocarpa* sites. (C) Low-frequency variance for all *Q. macrocarpa* sites. (D) Annual power production from 1961–2001 (Gigawatt hours) of the coal-fired generating station. Note: in A, B, and C, site S3O is indicated with thick, bold line, and site C2O is indicated with thin, bold line.

riod (1960–2000) was lowest for site S3O, a stand south of the station showing extensive crown die-back. All site chronologies showed similar year-to-year variation (*i.e.* wide and narrow growth years are corresponding across all sites) (Figure 2). In terms of the low-frequency variation, a number of sites showed below average growth starting around 1970, including the control site (Figure 2C). Only site S4O showed above average growth during this period, demonstrating the highest index values from 1980–2001.

Site S3O started to show decreased growth in 1974, whereas all sites exhibited low growth in 1976–1977 (Figure 2A); only site S3O showed a decrease in sensitivity after 1977, and did not fully recover. Growth at this site remained far below average following 1977, even though the high-frequency variation was still corresponding marginally with other sites (Figure 2B). The raw mea-

Figure 3. Raw measurement series (22 individual cores) from all *Q. macrocarpa* trees sampled at site S3O (transformed by a straight line through the mean), illustrating the simultaneous onset of radial growth decline *ca.* 1976–1977.

surement series for site S3O showed the synchronous onset of suppressed radial growth in all trees (Figure 3), suggesting that a change in the local environment occurred at that site. None of the other bur oak sites, regardless of proximity to the generating station, showed a radial growth decline similar to that observed in site S3O.

Correlations between the bur oak chronologies (straight line through the mean, low-frequency and high-frequency variation) and yearly production output were not significant for the period of 1961–2001. There was some correspondence of decreased radial growth and increased production levels in 1976–1977 and 1988 (Figure 2), however the control chronology also showed decreased growth at these times.

Coefficients for the correlation between bur oak chronologies of study plots with that of the bur oak control plot, prior to the onset of operations, were all significant except for one site, N2O (Table 3). Site N2O was comparatively younger than the control plot, and age effects are most likely responsible for this non-congruency. This verifies the use of the high-frequency control chronology as a reference chronology during the pollution period, as it showed correspondence with the other sites prior to the pollution source, yet would not have been affected by emissions. For the period of generating station operation (1961–2001), the strength of correlations between the study plots and control plot increased for the majority of the study plots (Table 3).

Trembling Aspen

The aspen chronology statistics were similar across all sites (Table 4). Relative to bur oak, trem-

Table 3. Pearson's correlation (r) and p -values for bur oak site residual chronologies (straight line through the mean) with the control plot residual chronology: prior to (1920–1960) and during operation of the generating station (1961–2001).

Site	1920–1960		1961–2001	
	r	p -value	r	p -value
N1O	0.42	0.006	0.47	0.002
N2O	0.27	ns	0.38	0.014
E1O	0.31	0.050	0.42	0.006
E3O	0.37	0.018	0.61	0.000
E4O	0.45	0.005	0.49	0.001
S1O	0.50	0.001	*0.41	0.009
S3O	0.42	0.007	0.43	0.005
S4O	0.72	0.000	*0.64	0.000
W1O	0.57	0.000	0.73	0.000
W2O	0.37	0.016	0.63	0.000
W3O	0.48	0.002	0.50	0.001

*Indicates a decrease in correlation during period of station operation. Note: N2O pre-operation period was 1937–1960; E4O pre-operation period was 1923–1960. ns = not significant.

bling aspen chronologies had larger mean ring widths, and higher values for both mean sensitivity and standard deviation. Mean ring width for the aspen chronologies was between 1.43 and 2.62 mm. All sites demonstrated substantially similar growth patterns during the period of coal-fired operation (Figures 4A, B, C), regardless of proximity to the generating station. No significant crown die-back was present in any of the sites, nor was any drastic radial growth decline. In the low-frequency component of growth, many of the sites demonstrated lower than average growth following 1970, including the control chronology (Figures 4A, C).

Correlation of the trembling aspen high-frequency component variance with yearly production output was not significant for any sites during the period of 1961–2001. Correlation of one of the trembling aspen standard chronologies (straight line through the mean) with yearly output was significant, as was one the low-frequency chronologies (*i.e.* two out of the total 63 correlations with yearly production were significant). However, the apparently significant correlations were contradictory, therefore no consistent correlation existed between radial growth and pollutant emission levels. There was correspondence of decreased radial growth and increased production levels in 1976–

Table 4. Statistics for all trembling aspen standard site chronologies resulting from detrending with a 20-year spline and for the common interval analysis.

Site	N2A		N3A		N4A		E1A		E2A		S2A		S4A		S5A		C1A	
Chronology length	1933–2001		1931–2001		1952–2001		1937–2001		1938–2001		1935–2001		1935–2001		1930–2001		1924–2001	
No. of trees	10	20	10	20	10	21	9	13	26	13	10	18	11	16	10	10	13	24
No. of radii	1.66	1.73	1.83	1.79	2.62	1.79	1.83	1.79	1.79	1.79	1.72	1.72	1.79	1.79	2.01	2.01	1.43	1.43
Mean ring width	0.26	0.29	0.34	0.42	0.33	0.34	0.34	0.42	0.42	0.42	0.22	0.22	0.23	0.23	0.27	0.27	0.35	0.35
Mean sensitivity	0.31	0.24	0.31	0.38	0.29	0.29	0.31	0.38	0.38	0.38	0.20	0.20	0.20	0.20	0.25	0.25	0.29	0.29
Standard deviation	0.12	0.06	0.05	0.03	0.17	0.17	0.05	0.03	0.03	0.03	0.14	0.14	0.07	0.07	0.13	0.13	0.12	0.12
First-order autocorrelation	Common Interval Analysis (1970–2000)																	
No. of trees	10	10	6	9	10	10	10	10	10	10	10	10	11	11	10	10	13	13
No. of radii	20	16	13	14	16	16	16	16	16	16	18	18	16	16	18	18	23	23
Variance in PC1 (%)	60.88	51.15	49.85	70.53	58.52	58.52	58.52	58.52	58.52	58.52	43.18	43.18	39.85	39.85	54.57	54.57	69.67	69.67
Interseries correlation	0.58	0.48	0.48	0.68	0.55	0.55	0.55	0.55	0.55	0.55	0.37	0.37	0.35	0.35	0.51	0.51	0.68	0.68
Mean sensitivity	0.29	0.30	0.30	0.32	0.34	0.34	0.32	0.34	0.34	0.34	0.26	0.26	0.28	0.28	0.24	0.24	0.40	0.40

Figure 4. (A) Standard chronologies for the *P. tremuloides* sites, standardized with a straight line through the mean. (B) High-frequency variance (standard chronology, resulting from a 20-year smoothing spline) for all *P. tremuloides* sites. (C) Low-frequency variance for all *P. tremuloides* sites. (D) Annual power production from 1961–2001 (Gigawatt hours) of the coal-fired generating station. Note: in A, B, and C, site C1A is indicated with a thin, bold line.

1977 (Figure 4), but the control chronology also showed decreased growth during this period.

Climatic Analysis

The first four PC axes explain 52.9, 15.8, 6.6, and 5.2% of the total variance present among all high-frequency site chronologies. The first two axes are presented here. The component scores for all sites on the first axis were positive, showing that patterns of radial growth are correlated among all site chronologies, regardless of species (Figure 5A). Year scores from the first axis (Figure 5B) were significantly negatively correlated with June temperature in the current growing season (Figure 6A). Year scores from the first axis were also significantly positively correlated with precipitation in the previous May and previous September, and negatively with precipitation in the current Feb-

Figure 5. (A) Site scores from the first component of the principal component analysis (PCA). Black bars indicate *Q. macrocarpa*, white bars indicate *P. tremuloides*. (B) Year scores from the first component of the PCA.

ruary (Figure 6B). On the second axis, all bur oak sites had negative loadings, while trembling aspen response was mostly positive, with the exception of site N4A (Figure 7A). Year scores from the sec-

Figure 6. Correlation coefficients between year scores and mean monthly temperature (A) and total monthly precipitation (B) for the period 1961–1999, previous May to current August. Dashed lines indicate significant correlations at $p < 0.05$.

Figure 7. (A) Site scores from the second component of the principal component analysis (PCA). Black bars indicate *Q. macrocarpa*, white bars indicate *P. tremuloides*. (B) Year scores from the second component of the PCA.

ond axis (Figure 7B) were significantly, positively correlated with temperature in the previous October (Figure 8A).

DISCUSSION

Radial Growth

If atmospheric deposition of sulphur dioxide was responsible for a growth decline, it is likely that many stands of a given species would show a marked decline at the same time (Van Deusen 1990). However, this was not found, with site S30 being the only site sampled in which a substantial radial decline was observed, and in which the majority of trees were either dead or dying. Although radial growth across both tree species was below average following 1970, this decrease was also present in the control chronologies, which would not have been affected by airborne emissions from the generating station. This radial growth decrease is therefore likely a result of age effects and stand dynamics. At breast height, the cambial age and the distance of the cambium from the photosyn-

Figure 8. Correlation coefficients between year scores and mean monthly temperature (A) and total monthly precipitation (B) for the period 1961–1999, previous May to current August. Dashed lines indicate significant correlations at $p < 0.05$.

thetic centers of the canopy increase over time (Cook and Innes 1989). The annual ring width also decreases as a tree ages, because the amount of new wood added each year is constant, while the circumference increases (Nash *et al.* 1975). This leads to a decrease in annual ring width with increasing age. Additionally, in closed canopy stands, the effects of competition increase as individual trees increase in size. Unlike the rapid growth associated with a release (*e.g.* death of an adjacent tree), growth decline caused by increasing competition appears to be gradual (Phipps 1984). Trembling aspen is a light-dependent species (Perala 1990), whereas bur oak has an intermediate light requirement (Johnson 1990), and therefore it is expected that these species would be in competition with surrounding canopy trees as they were in relatively even-aged stands. Slightly decreasing growth trends can be expected as tree crown competition increases (McClenahan and Dochinger 1985).

Although it is well established that increases in ambient sulphur dioxide levels are linked to decreased radial growth (*e.g.* Thompson 1981; Fox

et al. 1986), the emissions from this generating station were likely too low and discontinuous to have had a widespread deleterious effect on tree growth near the station. This generating station is quite small (132 MW) in comparison to other stations documented in the literature that show negative effects on tree growth (Gupta and Ghouse 1987; Muir and McCune 1988). Over the 40-year span of operations, emissions were significantly increased only at four different times, and in 1998 (the year of highest output, but only at 42% of the station capacity) the maximum annual predicted ground-level concentration of SO₂ was 0.58 µg/m³ (SENES 2001). It has been suggested that a long-term concentration threshold of 100–150 µg/m³ SO₂ will cause negative growth effects on forest trees (Roberts 1984), although a critical level of 20 µg/m³ SO₂ (annual mean) has been established in Europe for forest trees (Sanders *et al.* 1995). In comparison to these suggested thresholds, the levels of SO₂ in this study area were far below those of potential negative growth effects. Further, operations were historically less than 20% capacity on average, and increased operation was greatest during the dormant season (winter) and when stomatal conductance was likely reduced (drought). Coupled with the fact that bur oak and trembling aspen are tolerant or intermediate in tolerance to SO₂, any pollution effect would be very small and difficult to detect.

The decline in site S3O is likely related to urban development, with construction of a road immediately adjacent to the site, perpendicular to the direction of site drainage, occurring in 1977 (Springfield municipality office, personal communication 2002). This area is known to have a high water table (*e.g.* residents are unable to have basements in their houses), and interference with the natural drainage may have exaggerated the situation. Insufficient soil aeration may be a factor causing oak decline, with deficiencies in soil gas permeability reducing fine root formation and subsequently reducing the stress tolerance of trees (Gaertig *et al.* 2002). Soils that are waterlogged, compacted, or shallow have previously been implicated in oak decline (Wargo *et al.* 1983).

True controls are nearly impossible to obtain in tree-ring research because one can never assess

all possible sources of site variation. However, important information on natural variability can be gathered from carefully scrutinized sites that are outside the range of influence of pollutants (Nash and Kincaid 1990). Chronology congruency prior to operation was confirmed between the bur oak study plots and the control plot, and correlations with the control site chronology became stronger for most bur oak study sites during the period in which the generating station was operating. This stronger correspondence of radial growth trends with sites near the pollution source and the control site does not support a pollution effect; if a pollution effect existed, one would expect a decrease in correspondence (assuming that the controls had no pollution exposure).

There was some correspondence between years of increased emissions and years with reduced growth (1976–1977, 1988). The increased production at the Selkirk station (and therefore increased emission levels) in these years was in response to prolonged drought conditions, which reduced hydro-electrical generating capacity. Therefore, a comparison of the control chronology with sites near the station is necessary to determine if climatic extremes are primarily responsible for decreased radial growth. For both tree species, the control site also demonstrated reduced growth in these years. Further, in 1998 and 2000 (high-emission, non-drought years), there was no significant decrease in ring width; there was actually an increase in ring width in the aspen chronologies in 2000 (Figures 4A, B). This demonstrates that the decreased growth in 1976–1977 and 1988 is most likely a result of low precipitation levels and not increased emissions.

Climatic Analysis

Climatic variation is important in controlling the growth of both bur oak and trembling aspen in southeastern Manitoba. Growth of bur oak and trembling aspen in all sites was lowest in years with a hot June. High June temperature likely inhibits leaf expansion of both species, and subsequently affects radial growth. In a study on the radial growth of bur oak in Birds Hill Provincial Park (southern end of this study area) by Hanuta

(2002), a significant negative correlation was found between radial growth and temperature in May and June of the current year. This was also found with bur oak in eastern Nebraska, where current June temperature was negatively correlated with radial growth (Lawson *et al.* 1980). High May temperatures were found to be associated with smaller springwood vessels in bur oak in Virginia, and it was hypothesized that this was caused by the adverse effect of high temperatures and water stress at the time these large cells are expanding (Woodcock 1987).

Hogg *et al.* (2002) employed regression modeling of trembling aspen growth response to climate variation, and found that the climate moisture index (CMI), growing degree-days (GDD), and snow depth at the end of March were all significant regression coefficients. Precipitation in the current June and July were also found to be significant in a regression model, but the strength of the model was not as strong as with the CMI, GDD, and snow depth.

A clear differentiation between the two tree species was also observed. Bur oak sites all showed strong negative loadings on the second PC axis, indicating a positive relationship with May–July precipitation (although these correlations were not significant), and sensitivity to warmer temperature in the previous October. Bur oak is a ring-porous species, and as such begins cambial activity in the spring to transport water for photosynthesis before leaf emergence (Lechowicz 1984). Hanuta (2002) and Lawson *et al.* (1980) also noted a positive relationship between growth and precipitation in the spring for bur oak. Trembling aspen, a diffuse-porous species that demonstrates early and indeterminate leaf emergence, does not depend on early-season water availability to the same extent as ring-porous trees (Lechowicz 1984); its growth could be inhibited by increasing current growing season precipitation. Many of the sites in the study area have high-clay soils with restricted drainage. Any waterlogging of the soil could have a negative effect on aspen, which grows best on sandy, well-drained soils (Perala 1990). In terms of temperature in the previous October, warmer weather may lead to an increase in evaporation rates (Kozlowski and Pallardy 1997).

If a tree's transpiration is greater than its water absorption in the autumn, water stress will increase (Fritts and Shashkin 1995). This stress may be reflected in the following year's growth in bur oak, a ring-porous species, but not necessarily in trembling aspen.

Substrate composition may also be a factor in how bur oaks respond to precipitation, because of their drought-resistant nature (Lawson *et al.* 1980). The mean sensitivity (a measure of the relative differences in width between adjoining rings (Fritts 1976)) of trees in sites that are not well drained is expected to be lower as they are not as dependent on regular precipitation events. This is demonstrated by site S3O, having a loamy soil, a high water table (likely resulting from reduced site drainage) and a low sensitivity value. Conversely, site S4O, located two kilometers south of S3O, has a sandy loam soil with good drainage and showed higher sensitivity and higher mean ring width. Site S4O acted as a control for S3O, in that it too would have been expected to show a growth decline if airborne emissions were causing decline along the southern transect. Although pollution has been shown to change a tree's growth-climate response (LeBlanc 1993), it seems that age effects and site factors (such as the drainage regime) were of more influence in this study. Unless changing growth-climate responses are apparent along a supposed pollution gradient (*e.g.* Thompson 1981), which was not the case in this study, no conclusions can be made with respect to adverse pollution effects on growth.

CONCLUSIONS

Emissions from the coal-fired generating station do not appear to be linked to decline observed south of the station, but rather the decline in S3O was likely a result of poor site conditions (*i.e.* poor drainage following the construction of a road), whereas the below-average growth seen in 1970–2001 across most stands seems attributable to age effects. As the radial growth of both bur oak and trembling aspen in southern Manitoba was found to be significantly related to climate, it should be considered an important natural stress factor in future forest health studies in the area. Tree-ring

analysis has proved to be effective in determining the onset of decline in a bur oak stand in this study (*i.e.* decline started far earlier than 1998 or 2000, the years with increased emission levels that residents were concerned had negatively affected tree growth), and that decline was not linked to emissions from the local generating station.

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