

MODEL

# EFFECTS OF TROPOSPHERIC O<sub>3</sub> ON TREMBLING ASPEN AND INTERACTION WITH CO<sub>2</sub>: RESULTS FROM AN O<sub>3</sub>-GRADIENT AND A FACE EXPERIMENT

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**Abstract.** Over the years, a series of trembling aspen (*Populus tremuloides* Michx.) clones differing in O<sub>3</sub> sensitivity have been identified from OTC studies. Three clones (216 and 271 [O<sub>3</sub> tolerant] and 259 [O<sub>3</sub> sensitive]) have been characterized for O<sub>3</sub> sensitivity by growth and biomass responses, foliar symptoms, gas exchange, chlorophyll content, epicuticular wax characteristics, and antioxidant production. In this study we compared the responses of these same clones exposed to O<sub>3</sub> under field conditions along a natural O<sub>3</sub> gradient and in a Free-Air CO<sub>2</sub> and O<sub>3</sub> Enrichment (FACE) facility. In addition, we examined how elevated CO<sub>2</sub> affected O<sub>3</sub> symptom development. Visible O<sub>3</sub> symptoms were consistently seen (5 out of 6 years) at two of the three sites along the O<sub>3</sub> gradient and where daily one-hour maximum concentrations were in the range of 96 to 125 ppb. Clonal differences in O<sub>3</sub> sensitivity were consistent with our OTC rankings. Elevated CO<sub>2</sub> (200 ppm over ambient and applied during daylight hours during the growing season) reduced visible foliar symptoms for all three clones from 31 to 96% as determined by symptom development in elevated O<sub>3</sub> versus elevated O<sub>3</sub> + CO<sub>2</sub> treatments. Degradation of the epicuticular wax surface of all three clones was found at the two elevated O<sub>3</sub> gradient sites. This degradation was quantified by a coefficient of occlusion which was a measure of stomatal occlusion by epicuticular waxes. Statistically significant increases in stomatal occlusion compared to controls were found for all three clones and for all treatments including elevated CO<sub>2</sub>, elevated O<sub>3</sub>, and elevated CO<sub>2</sub> + O<sub>3</sub>. Our results provide additional evidence that current ambient O<sub>3</sub> levels in the Great Lakes region are causing adverse effects on trembling aspen. whether or not elevated CO<sub>2</sub> in the future will alleviate some of these adverse effects, as occurred with visible symptoms but not with epicuticular wax degradation, is unknown.

Key words: ozone, carbon dioxide, FACE, aspen, greenhouse gases, climate change, gradients

## 1. Introduction

Global atmospheric concentrations of the greenhouse gases carbon dioxide (CO<sub>2</sub>) and tropospheric ozone (O<sub>3</sub>) are increasing at the rate of 1 to 2% per year (Keeling et al., 1995; Mohnen et al., 1993). While elevated CO<sub>2</sub> tends to enhance tree photosynthesis and growth and to increase water use efficiency (Ceulemans and Mosseau, 1994), O<sub>3</sub> is a highly phytotoxic gas that impacts forest trees (Barnard et al., 1991; Chappelka and Samuelson, 1998; Hogsett et al., 1997). Treshow (1970) and Treshow and Stewart

(1973) were the first to demonstrate that trembling aspen (*Populus tremuloides* Michx.) is sensitive to  $O_3$ . The strong genetic control involved in aspen's response to  $O_3$  was first shown by Karnosky (1976, 1977). Subsequent aspen studies have: documented decreased growth under ambient  $O_3$  conditions (Wang *et al.*, 1986); developed dose response relationships for growth responses (Karnosky *et al.*, 1992a, b; Karnosky *et al.*, 1996; Karnosky *et al.*, 1998); characterized the physiological mechanisms for  $O_3$  responses of aspen (Gagnon *et al.*, 1992; Coleman *et al.*, 1995a, b; Coleman *et al.*, 1996); documented population differences in  $O_3$  tolerance (Berrang *et al.*, 1986, 1989, 1991); and implicated superoxide dismutase in  $O_3$  tolerance (Sheng *et al.*, 1997; Karnosky *et al.*, 1998).

In contrast to their response to  $O_3$ , *Populus* species generally respond positively to increases in  $CO_2$  concentrations. Increases in individual leaf area, whole crown leaf area, leaf area duration, and leaf area index have been observed in *Populus trees* grown in elevated  $CO_2$  (Ceulemans *et al.*, 1994; Curtis *et al.*, 1995). Aspen grown in twice ambient  $CO_2$  had greater photosynthetic rates and a greater whole plant photosynthesis because of increased photosynthetic rates in the lower half of the crown (Kubiske *et al.*, 1997).

Given that both tropospheric  $O_3$  and  $CO_2$  are likely to continue to increase into the foreseeable future, the need for a better understanding of the complex interaction of  $CO_2$  and  $O_3$  on forest ecosystems is obvious (Volin and Reich, 1996). However, relatively little research has been done to characterize the interacting effects of  $O_3$  and  $CO_2$  for trees (Barnes and Wellburn, 1998). Kull *et al.* (1996) reported that elevated  $CO_2$  (150 ppm over ambient) increased  $O_3$  susceptibility of two aspen clones exposed to  $O_3$  as determined by photosynthetic responses. However, subsequent evaluation of growth responses of the same aspen clones suggested that elevated  $CO_2$  (150 ppm over ambient) did not exacerbate the  $O_3$  effects as predicted from Kull's work, but it also did not ameliorate the adverse effects of  $O_3$  on plant growth over a three-year time period with plants growing in natural soil in OTCs (Karnosky *et al.*, 1998). In contrast, Volin and Reich (1996) and Volin *et al.* (1998) reported that elevated  $CO_2$  (300 ppm over ambient) ameliorated  $O_3$  effects for young aspen plants grown for 58 or 101 days in pots in growth chambers.

Two novel methods for studying the effects of  $O_3$  on aspen ecosystems are described in this paper. First, aspen clones differing in  $O_3$  sensitivity were established in plantations at three locations differing in their ambient  $O_3$  characteristics (41 to 70.4 ppmh in SUMO [the sum of daylight hourly  $O_3$  concentrations] from June 1 to August 30, 1996). Second, a Free-Air  $CO_2$  and  $O_3$  Enrichment (Aspen FACE) experiment near Rhinelander, Wisconsin, was established where aspen clones differing in  $O_3$  and/or  $CO_2$  sensitivity were planted in a FACE system capable of accurately and reliably dispensing  $CO_2$  and/or  $O_3$ .

## 2. Methods

### 2.1. THE $O_3$ GRADIENT STUDIES

In 1993, we established three types of aspen plantations at each of three locations (Rhinelander, Wisconsin - low  $O_3$ ; Kalamazoo, Michigan - intermediate  $O_3$ ; and Kenosha, Wisconsin - high  $O_3$ ) along a natural  $O_3$  gradient in the Lake States (Fig. 1).

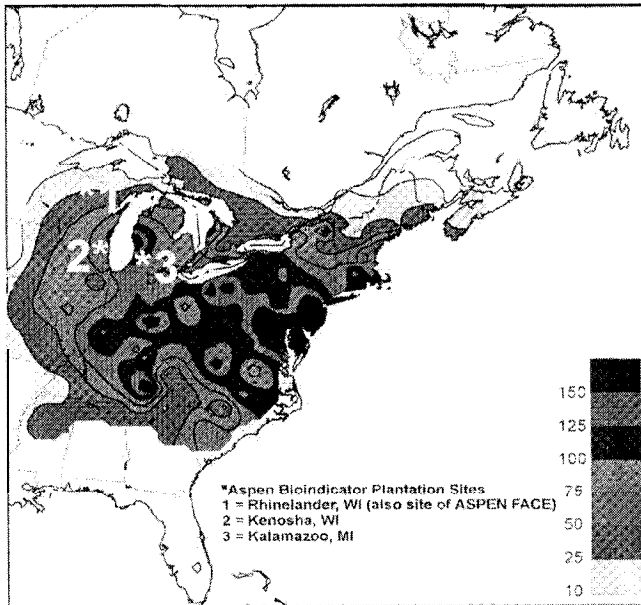


Fig. 1. Spatial distribution of average hours with O<sub>3</sub> >82 ppb (1986-1993) (from: Dann and Summers, 1997) and locations of aspen plantations (1, 2, 3).

At each location, we established three experiments. The first was a “common garden” experiment of 7 aspen clones differing in O<sub>3</sub> sensitivity (clones 1, 253 and 259 = O<sub>3</sub> sensitive; clones 10, 216, 221, and 271 = O<sub>3</sub> tolerant [Karnosky, 1976; Karnosky *et al.*, 1992a]). This experiment consisted of individual trees of each clone planted at 2 m x 2 m spacing and there were 10 replicates at each site. In the second experiment, we established a “growth and yield” trial with O<sub>3</sub> tolerant clone 216 and O<sub>3</sub> sensitive clone 259 planted in 16 tree (4 x 4) blocks at 2 m x 2 m spacing between trees and with six replicates. The final experiment at each site was a “competition trial” between clones 216 and 259 where trees were planted at 0.5 m x 0.5 m between trees and 100 tree (10 x 10) blocks were established in either pure clonal blocks or mixed clonal blocks (the O<sub>3</sub> sensitive and tolerant clones were alternately spaced in this part of the plantation). Again, six replicates were used at each site. Two border rows of clone 271 were established around each of the three plantations at each site.

Weeds were controlled around all trees by herbicide application in the first season and then mowing in subsequent years until weed competition was no longer a problem. All trees were measured annually and also observed at least once per season for visible foliar symptoms. All three sites were old field sites that had not been in agricultural use for several years previously. The sites all have sandy loam soils with relatively high fertility. Temperature and rainfall patterns from the three sites suggest that they are not widely different in summer climate (Table I). Each site was enclosed in a 3 m tall deer fence. O<sub>3</sub> has been monitored independently and continuously at the Kenosha site and Rhinelander site by the Wisconsin Department of Natural Resources. The Kalamazoo site was monitored for O<sub>3</sub> by the Pharmacia-Upjohn Company about 0.5 km from our aspen site. The O<sub>3</sub> data was quality assured and was part of the AIRS (Aeometric Information and Retrieval Systems of the U.S. Environmental Protection Agency) network. A summary of the O<sub>3</sub> values for 1995-1997 are shown in Table II.

TABLE I

Comparisons of monthly mean temperatures ( $^{\circ}\text{C}$ ) and seasonal total rainfall (cm) at our three aspen sites along a natural  $\text{O}_3$  gradient (from: <http://www.acdc.noaa.gov/online>).

	Average Monthly Temperatures (deg. C)								
	1995			1996			1997		
	Kala	Keno	Rhine	Kala	Keno	Rhine	Kala	Keno	Rhine
June	23.38	21.57	21.98	22.38	17.95	18.00	21.97	17.98	19.60
July	25.37	23.37	21.83	22.95	20.75	17.88	23.05	20.61	19.55
<b>Aug</b>	25.89	23.92	<b>21.78</b>	24.35	22.33	20.08	21.68	19.26	16.81

June through August Rainfall (cm)			
Date	Kalamazoo	Kenosha	Rhineland
1995	26.58	19.64	20.17
1996	30.48	39.10	35.43
<b>1997</b>	29.58	38.17	24.12

TABLE II

Summary of  $\text{O}_3$  values at the three locations where we have aspen **bioindicator** plots for 1995 to 1997.

Site	1995			1996			1997		
	1-hr Max (ppb) (June- Aug)	SUM 0 ppmh (June- Aug) 8 a.m.-8 p.m.	SUM 06 ppmh (June- Aug) 24 hr.	1-hr Max (ppb) (June- Aug)	SUM 0 ppmh (June- Aug) 8 a.m.- 8 p.m.	SUM 06 ppmh (June- Aug) 24 hr.	1-hr Max (ppb) (June- Aug)	SUM 0 ppmh (June- Aug) 8 a.m.4 p.m.	SUM 06 ppmh (June- Aug) 24 hr.
Rhineland, WI	79	37.1	4.1	85	41.0	2.5	80	40.6	4.1
Kalamazoo, MI	125	48.0	20.6	106	47.3	17.3	96	53.8	25.7
Kenosha, WI	120	59.5	29.8	122	70.4	15.1	112	58.7	10.7

We evaluated **foliar** injury on all leaves on a subset of the trees representing all the clones at the  $\text{O}_3$  gradient sites. Foliage from a subset of the trees representing all clones at the  $\text{O}_3$  gradients sites was collected for wax composition analyses in August of 1995, 1996, 1997, and 1998. Leaf segments (5 mm x 10 mm) were air dried, **gold-**coated on a cold stage, and examined under a JSM 6400 SEM. Two hundred stomates per clone, per site were evaluated for occlusion.

## 2.2 THE ASPEN FACE STUDY

The Forest Atmospheric Carbon Transfer and Storage (FACTS 2) Free-Air CO<sub>2</sub> and O<sub>3</sub> Enrichment (Aspen FACE) facility was located at the USDA Forest Service, Harshaw Experimental Farm near Rhinelander, Wisconsin. The study encompassed 32 ha of land with twelve 30 m diameter treatment rings spaced 100 m apart within a deer-fenced area. The 12 rings were composed of 3 control rings, 3 rings with elevated O<sub>3</sub>, 3 rings with elevated CO<sub>2</sub>, and 3 rings with elevated O<sub>3</sub> + elevated CO<sub>2</sub>. Ozone was administered during the daylight hours according to the 1.5x profile for the lower Great Lakes region as described by Karnosky et al. (1996). This profile was a modified ambient profile developed from the 1987 O<sub>3</sub> data for Washtenaw County, Michigan. It was modified to more closely fit the 6-year averages documented by Pinkerton and Lefohn (1987). We only fumigated during appropriate weather conditions, i.e. we avoided fumigating on cool days (<15°C) or during rain, fog, or dew events. Ozone was monitored by Thermo Environmental Instruments Inc. Model 49C monitors adapted for rapid response times (4 sec) and calibrated weekly. CO<sub>2</sub> was administered during daylight hours at 560 ppm, which was about 200 ppm above the ambient level of CO<sub>2</sub>. CO<sub>2</sub> was monitored with Licor Inc. LI-6252 CO<sub>2</sub> analyzers and calibrated weekly.

The Aspen FACE gas dispensing apparatus was modified from that developed by Lewin et al. (1994) and Nagy et al. (1994). In order to accommodate both CO<sub>2</sub> and O<sub>3</sub> from our vertical vent pipes, we modified our gas injection system in two ways compared to that system used at the FACTS I (Duke) experiment with loblolly pine (Hendrey et al., 1998). First, to accommodate a larger flow rate to dilute O<sub>3</sub> concentrations coming out of the vertical vent pipe (to minimize O<sub>3</sub> concentrations near the vertical vent pipes), we changed from a hole configuration to a slot. We oriented the vertical vent pipe so the slot was pointed away from the center of the ring and placed a set of baffles to redirect air coming from the vertical vent pipes into the FACE ring. Finally, we added a flashing on top of the baffles to direct air down and into the ring (Walklate et al., 1996). Together, these modifications improved the stability and distribution of both CO<sub>2</sub> and O<sub>3</sub> in our FACE rings and minimized CO<sub>2</sub> usage. CO<sub>2</sub> was distributed from the central storage tanks to each FACE ring through copper pipe. O<sub>3</sub> was generated from pure oxygen with a Praxair O<sub>3</sub> generator capable of producing 18-30 lbs. of O<sub>3</sub> per day. The O<sub>3</sub> was dispensed to the FACE rings through stainless steel tubing. Three controlling microcomputers were used to control the opening and closing of the valves at each ring and to control release of CO<sub>2</sub> and/or O<sub>3</sub> into the rings. CO<sub>2</sub> and O<sub>3</sub> were dispensed from the upwind side of each ring and monitored at plot centers.

Each Aspen FACE ring was divided into two halves by a central walkway. One half of each ring was planted at 1 m x 1 m with 1-year-old plants of five trembling aspen genotypes differing in O<sub>3</sub> sensitivity (8L, 216 and 271 = O<sub>3</sub> tolerant; and 42E and 259 = O<sub>3</sub> sensitive). Each clone was planted in two-tree plots randomly located in the one half ring. This resulted in 30 to 35 trees per clone being in the sweet spot where CO<sub>2</sub> and O<sub>3</sub> were close to target values ( $\pm 10\%$  for 1 minute averages). The other one half of the ring was divided into two sections: one planted with aspen clone 216 (O<sub>3</sub> tolerant) and sugar maple (*Acer saccharum* Marsh.) seedlings intermixed at 1 m x 1 m spacing, and the other with aspen clone 216 and paper birch (*Betula*

*papyrifera* Marsh.) intermixed at 1 m x 1 m spacing. There are five border rows of aspen around each FACE ring. An irrigation system was used to supplement rain events during the first two growing seasons. It was used on four occasions in 1997 and six times in 1998 after periods of extended dry conditions to assure establishment of the trees. Soil tensiometers were used to evaluate when watering was needed. All trees were planted from 1-year-old stock in July, 1997 and treatments with CO<sub>2</sub> were run from August 15 to September 30, 1997. CO<sub>2</sub> treatments resumed on May 1, 1998 and O<sub>3</sub> treatments started on May 15, 1998. Both CO<sub>2</sub> and O<sub>3</sub> treatments were stopped on October 12, 1998. The treatments were timed to have CO<sub>2</sub> exposures from budbreak to budset for trembling aspen.

We thoroughly characterized all plants in our FACE study. They were all measured at the time of planting and at the end of the first growing season. A subset of intensively sampled trees were used for characterizing seasonal growth, crown architecture, and physiological characteristics. We sampled foliage from sample leaves of clones 216, 259 and 271 for SEM in August of 1997 and 1998 as previously described. Visible foliar symptoms were scored on June 1, July 1, August 1, and September 1, 1998.

### 3. Results and Discussion

Visible foliar symptoms for aspen have not been detected at the clean-air (Rhinelander) gradient plot or in the control and elevated CO<sub>2</sub> treatments in the FACE experiment. However, visible foliar symptoms were seen in five out of six years (no symptoms were seen in 1998) at the higher O<sub>3</sub> (Kalamazoo and Kenosha sites) and in the O<sub>3</sub> and O<sub>3</sub> + CO<sub>2</sub> FACE treatments in 1998. Symptomatic leaves were those showing black bifacial necrosis, chlorosis, or upper leaf surface black or red stipple (Karnosky et al., 1996). Young leaves did not show symptoms and recently mature leaves (LPI 6-10, Larson and Isebrands, 1970) showed most pronounced symptoms. Older leaves (LPI 15-20 or more) often showed multiple symptoms and secondary pests so they were more difficult to diagnose.

Foliar symptom data for a typical year at the gradient plots is shown in Table III and at the FACE site is shown in Table IV. At both of the higher O<sub>3</sub> gradient sites and in the FACE experiment, clone 259 was the most sensitive clone. This is consistent with previous research from OTCs (Karnosky et al., 1996). Relatively, symptoms were worse in the O<sub>3</sub> treatments in the FACE experiment. The seasonal 12-hr. daylight O<sub>3</sub> doses that induced the symptoms ranged from 47.3 to 70.4 ppmh at the gradient sites and from 57.6 to 60.7 ppmh (AOT 40 values at the FACE study were 25.8 to 30.7 ppmh) at the FACE experiment (Table V). These data are consistent with previous OTC results where visible foliar injury was seen on 50% of all leaves on O<sub>3</sub>-sensitive clones at 50 to 60 ppmh (Karnosky et al., 1996). Elevated CO<sub>2</sub> in the FACE experiment resulted in a decreased amount of visible foliar symptoms in all three clones. This is consistent with the results of Volin and Reich (1996) and Volin et al. (1998) who found that elevated CO<sub>2</sub> ameliorates the effects of O<sub>3</sub> on photosynthesis and growth in aspen. It is contrary to our previous results which suggested no amelioration (Kull et al., 1996) in OTCs. The level of CO<sub>2</sub> was higher in our FACE experiment (ambient + 200 ppm) versus our OTC work (ambient + 150 ppm). In

addition, the soil at the FACE site is considerably higher in N than that in our OTC site. Either of these two factors could have caused the difference between our OTC and FACE results with the same clones.

TABLE III

Summary of the percentage of leaves per tree showing visible injury (% L.I.) for O<sub>3</sub> and presence of sooty mold fungus (*Alternaria* spp.) on three aspen clones scored in August, 1996 at the three O<sub>3</sub> gradient sites. Means are of 20 trees per clone. Clones with the same first letter were not different ( $p < 0.05$ ) from one another within each site and clones with the same second letter were not different ( $\alpha < 0.05$ ) between sites as determined by the Student-Newman-Keuls multiple comparisons test.

Location	Clone	% L.I. <sup>1</sup> (O <sub>3</sub> ) ± SE.	% L.I. <sup>1</sup> (Sooty mold) ± S.E.
Rhineland	216	0 ± 0a, x	0 ± 0 a, x
	259	0 ± 0a, x	0 ± 0 a, x
	271	0 ± 0a, x	0 ± 0 a, x
Kalamazoo	216	8.2 ± 1.8 a, y	0 ± 0 a, x
	259	34.7 ± 2.8 b, y	21.0 ± 3.3 b, y
	271		
Kenosha	216	5.0 ± 1.9 a, y	10.6 ± 2.6 a, y
	259	43.1 ± 4.2 c, y	55.6 ± 4.8 b, z
	271	16.5 ± 1.8 b, y	13.0 ± 1.8 a, y

<sup>1</sup>Percentage of leaves affected by O<sub>3</sub> or sooty mold fungus.

TABLE IV

Percent leaves showing visible injury on August 1, 1998 for three trembling aspen clones varying in O<sub>3</sub> tolerance in the O<sub>3</sub> or O<sub>3</sub> + CO<sub>2</sub> treatments of the FACTS 2 (Aspen FACE) project in Harshaw, Wisconsin. Each replicate is the mean of at least 30 trees. Clones with the same first letter were not different ( $p < 0.05$ ) from one another for that treatment and clones with same second letter were not different between treatments as determined by the Student-Newman-Keuls multiple comparisons test.

Clone	O <sub>3</sub> Tolerance	Ozone				Ozone + CO <sub>2</sub>			
		Rep 1	Rep 2	Rep 3	$\bar{x}$	Rep 1	Rep 2	Rep 3	$\bar{x}$
216	tolerant	17.8	12.7	24.1	18.4 b, y	5.2	4.5	8.1	5.9 b, x
259	sensitive	55.3	51.1	57.8	54.7 c, y	33.1	37.7	41.9	37.6 c, x
271	tolerant	11.5	4.5	30.0	15.3 a, y	0	0	1.6	0.5 a, x

We found evidence of a secondary pathogen on trees impacted by O<sub>3</sub> at two of our O<sub>3</sub> gradient plots. A sooty mold fungus (spp.) occurred on a large number of leaves on the O<sub>3</sub> sensitive clone 259 at both the Kalamazoo and Kenosha sites. We believe this may have been associated with the degradation of the leaf epicuticular waxes visible under SEM (Figure 2). Epicuticular wax deposits on all three clones were unaltered at the Rhineland site but modified at the Kalamazoo and Kenosha sites. Waxes were platelike rather than crystalline and stomates were occluded by amorphous deposits on leaves collected from these sites. Effects appeared to be most dramatic at the Kenosha site in all three years and enhanced on the most O<sub>3</sub> sensitive clone (259). This modification resulted from changes in wax synthesis induced by O<sub>3</sub> (Percy *et al.*, 1998).

TABLE V

Mean ozone concentration (ppb) for the 7 a.m. to 7 p.m. time interval and AOT40 (ppmh) for 24 hrs per day for ambient air and the 3 O<sub>3</sub> and 3 O<sub>3</sub> + CO<sub>2</sub> treatments of the FACTS 2 (Aspen FACE) project in Harshaw, Wisconsin, for the period from May 1 to August 31, 1998.

Treatment	Rep	May		June		July		August		Season	
		Mean (ppb)	AOT 40 (ppmh)	Mean (ppb)	AOT 40 (ppmh)	Mean (ppb)	AOT 40 (ppmh)	Mean (ppb)	AOT 40 (ppmh)	Mean (ppb)	AOT 40 (ppmh)
O <sub>3</sub>	1	52	5.6	55	6.7	57	7.6	59	6.9	54.7	26.8
O <sub>3</sub>	2	54	6.5	57	7.8	58	8.3	58	8.1	56.3	30.7
O <sub>3</sub>	3	53	6.2	55	6.9	56	7.1	59	7.0	54.7	27.2
O <sub>3</sub> +CO <sub>2</sub>	1	52	6.1	55	7.3	55	7.1	64	9.2	54.0	29.7
O <sub>3</sub> +CO <sub>2</sub>	2	53	6.3	57	7.9	57	7.8	62	8.3	55.7	30.3
O <sub>3</sub> +CO <sub>2</sub>	3	50	5.2	55	6.7	57	7.4	57	6.5	54.0	25.8
Ambient		41	2.2	33	0	30	0	29	0.2	34.6	2.4

To quantify the degree of epicuticular wax degradation, we examined leaves from the three aspen clones (216, 259, 271) in the four Aspen FACE treatments and at the highest O<sub>3</sub> (Kenosha) gradient plot (Figure 3). We developed a coefficient of occlusion based on the degree of stomates covered by amorphous wax deposits with 0 = no occlusion and 4 = total occlusion. The Kenosha site had the highest coefficient of occlusion for all three clones. This was particularly interesting because no visible foliar symptoms were present in 1998 at the Kenosha site. This shows the value of epicuticular waxes as a very sensitive bioindicator of O<sub>3</sub> and/or CO<sub>2</sub> effects. At the FACE site, we saw significantly increased stomatal occlusion with all three treatments (CO<sub>2</sub> + O<sub>3</sub>, CO<sub>2</sub>, and O<sub>3</sub>) as compared to controls. While O<sub>3</sub> has been commonly reported to induce wax degradation (Percy *et al.*, 1990) and stomate occlusion (Huttunen, 1990), we believe this is the first report of increased wax occlusion of stomates in elevated CO<sub>2</sub>.

We compared the relative photosynthetic rates under control (ambient CO<sub>2</sub>) and elevated CO<sub>2</sub> treatments in the FACE treatments in 1997 (Table VI). As can be seen, elevated CO<sub>2</sub> significantly increased the maximum light saturated photosynthesis. We compared aspen from our FACE site to OTC data (Coleman *et al.*, 1995), field-grown seedlings (Roden and Pearcy, 1993), and to potted plants grown in the biotron (Volin *et al.*, 1998). Our FACE rates of photosynthesis were much higher than our previous OTC results. In addition, the biotron-grown plants (Volin *et al.*, 1998) were the least productive photosynthetically. The differences could be due to different light intensities. Light levels are generally lower in the biotron (Olsyk *et al.*, 1986) and light is also decreased significantly (about 12% lower on average) in OTCs (Heagle *et al.*, 1996). The N levels in the various studies could also have affected the photosynthetic rates as photosynthesis is linearly related to N levels in aspen (Coleman *et al.*, 1998).



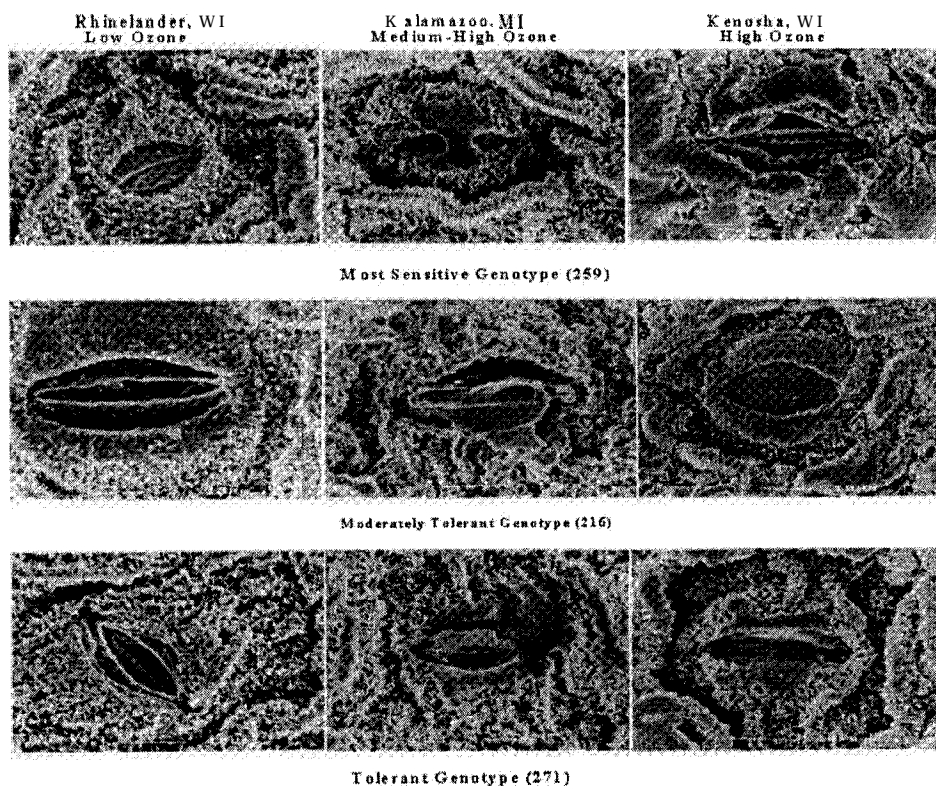


Fig. 2. Relationship between 1997 leaf surface wax structure and ozone levels in three aspen genotypes of differing O<sub>3</sub> sensitivities growing in 4-year-old plantations we established along a natural ozone gradient through Wisconsin and Michigan. Note: There was no visible foliar injury on the leaves in this composite photograph.

#### 4. Summary and Conclusions

We present evidence suggesting that ambient O<sub>3</sub> concentrations in the lower Great Lakes region of the United States are inducing visible foliar symptoms and epicuticular wax degradation on trembling aspen. This evidence is from two novel experimental methods. First, we examined the response of three aspen clones varying in O<sub>3</sub> sensitivity and that had been established in replicated trials along a natural O<sub>3</sub> gradient. Second, we examined the response of the same three aspen clones in a Free-Air CO<sub>2</sub> and O<sub>3</sub> Enrichment (FACE) facility. The O<sub>3</sub>-induced visible foliar symptoms were consistent among and between clones for the two experiments and consistent with our previous rankings. Elevated CO<sub>2</sub> in the FACE study decreased visible foliar injury suggesting an amelioration of O<sub>3</sub> effects by CO<sub>2</sub> for aspen. However, for epicuticular wax degradation, elevated O<sub>3</sub> at the two elevated O<sub>3</sub> sites and in the FACE experiment consistently degraded the aspen wax surface and this effect was not ameliorated by elevated CO<sub>2</sub>. In fact, elevated CO<sub>2</sub> alone appeared to negatively impact aspen epicuticular waxes.

TABLE VI

Photosynthesis light response parameters (means  $\pm$  se) of *Populus tremuloides* trees grown in the FACTS 2 experiment under ambient field conditions (ambient) and under free-air CO<sub>2</sub> enrichment (elevated). For comparison, other published results are shown for these same *P. tremuloides* clones grown under elevated CO<sub>2</sub> in OTCs (Coleman *et al.*, 1995b), and for unspecified, biotron-grown seedlings (Volin *et al.*, 1998) and unspecified field trees of *P. tremuloides* (Roden & Pearcy, 1993). Parameters are: light saturated photosynthesis rate ( $A_{\text{sat}}$ ,  $\mu\text{mol m}^{-2}\text{s}^{-1}$ ), dark respiration rate (Rd,  $\mu\text{mol m}^{-2}\text{s}^{-1}$ ), light compensation point (LCP,  $\mu\text{mol m}^{-2}\text{s}^{-1}$ ), apparent quantum yield ( $\phi$ ,  $\mu\text{mol mol}^{-1}$ ). Significant differences ( $p < 0.05$ ) among treatments from the FACTS 2 experiment are indicated by (\*) with  $n = 3$  as determined by a simple t test in Systat.

	Volin <i>et al.</i> , 1998 (Biotron)		Ambient		FACTS 2 (FACE)	
	Ambient CO <sub>2</sub>	Elevated CO <sub>2</sub>	Coleman <i>et al.</i> , 1995 (OTCs)	Roden & Pearcy, 1993 (field)	Ambient CO <sub>2</sub>	Elevated CO <sub>2</sub>
$A_{\text{sat}}$	5.8	7.8	8.5 $\pm$ 0.6	c. 15	21.6 $\pm$ 1.1	30.8 $\pm$ 1.4 *
Rd			1.8 $\pm$ 0.1	1.7 $\pm$ 0.2	3.8 $\pm$ 0.2	2.9 $\pm$ 0.2 *
LCP			48 $\pm$ 6	71 $\pm$ 7	33 $\pm$ 3	21 $\pm$ 1 *
$\phi$			51 $\pm$ 5	27 $\pm$ 2	68 $\pm$ 4	74 $\pm$ 6

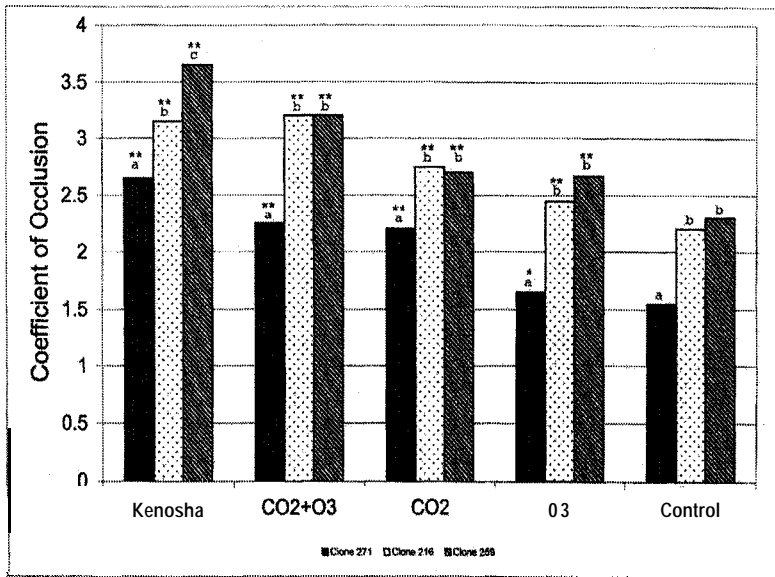


Fig. 3. Coefficient of occlusion as determined by scanning electron microscopy for the four treatments at the Aspen FACE (CO<sub>2</sub> + O<sub>3</sub>, CO<sub>2</sub>, O<sub>3</sub>, and control) and at the Kenosha site for three trembling aspen clones sampled in August, 1998. 0 = no occlusion; 4 = almost totally occluded by leaf surface waxes. Each FACE treatment value was the mean of 100 stomates per clone for each of 3 replicates and the Kenosha data is from 100 stomates of each clone. Significant differences from control values are shown by \* ( $p < 0.05$ ) and \*\* ( $p < 0.01$ ) and significant differences ( $p < 0.05$ ) between clones for a given treatment are indicated by letters as determined by the nonparametric Kohnogorov-Siminov test (Mylivec, 1957 and Smelko, 1991).

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