The North American ozone air quality standard: efficacy and performance with two northern hardwood forest tree species

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Abstract In many forested regions of North America, background O_3 levels have been rising despite the fact that hourly maximum concentrations have been decreasing. Unlike Europe, where critical levels based on a response threshold are used to assess risk, Canada and the United States use the best available scientific knowledge balanced by social, economic and political considerations to establish ambient air quality standards for air quality compliance purposes. These ambient air quality standards do not assume the existence of a concentration threshold. The United States (1997) and Canada (2000) established the O_3 standard as the 3-year average of the annual fourth highest daily maximum 8-hour O_3 concentrations, with target values set at 65 ppb and 80 ppb, respectively. Here, we use 5 years of basal area growth in one control and one O_3 Aspen FACE ring to evaluate the performance of five O_3 indices including AOT40 and the North American air quality standard. With our data, this standard outperformed AOT40, SUM60, SUM00 and 1-hour maximum as a single predictor of growth response. We also evaluate the potential of a standard-based, simple dose response function developed from Aspen FACE to predict productivity in *Populus tremuloides* and *Betula papyrifera*.

1. Introduction

Tropospheric ozone (O_3) continues to rise globally (Houghton et al., 2001). These changes in spatial patterns are being forced by changing demographics, economic activity, weather and climate. In the United States (US) during 1983–2002, there were large (-22%) decreases in national peak 1-hour O_3 concentrations. More recently (1993–2002), national 1-hour O_3 levels have improved but less rapidly (-2%) (USEPA, 2005). However, the national trend in 8-hour O_3 concentrations has decreased less (-14%) than the 1-hour, and levels during the past 10 years (1993–2002) have actually increased 4% across the same 370 sites. However, although 1-hour levels have decreased since 1983 by 26% at urban sites and 23% at suburban sites (where O_3 is highest), in 2002 O_3 levels were only 16% lower at rural sites. In 2002, for the sixth consecutive year, rural levels were greater than those than at suburban sites (USEPA, 2005). Ozone concentrations are on the increase in some urban areas of the US, and there is also a clear upward trend in many Canadian urban areas. Increasing emissions of O_3 precursors and a warming climate may be expected to continue to increase O_3 transport from urban/suburban areas to rural and forested areas.

A recent review (Percy et al., 2003) provides insight into the current impacts and O_3 threat to North American forests. It is clear that effects have been induced in diverse forest types across a large geographic area. Yet, although the processes leading to O_3 formation are relatively well understood, and the rate of O_3 deposition can be calculated, quantifying risk remains problematic due to uncertainties around the magnitude of flux into the plant. This unknown is, of course, a major impetus behind the intensified European effort to develop flux-based critical levels to assess risk to forests (see Karlsson et al., 2003). Unlike Europe, critical levels are not used in North America. Indeed legally based (US) and non legally based (Canada) air quality standards are used to regulate or control O_3 levels (see Percy et al., 2003). Best available scientific knowledge, balanced by social, economic and political considerations, is used to set ambient air quality standards. Currently, both countries use the same metric to calculate O_3 levels: namely, the 3-year average of the annual 4th highest daily maximum 8-hour average O_3 concentration. The target levels are set at 80 ppb (US National Ambient Air Quality Primary Stândard for human health) and 65 ppb (Canada Wide Standard for human health) (Federal Register, 1997; CCME, 2000).

Krupa et al. (2003) hypothesized that a predictive model could be developed using meteorology related to O_3 flux, and other variables associated with regulation of uptake that would provide a first-order approximation of flux. We believed this to be true and, given the appropriate long-term manipulative O_3 experiment where effects and meteorology were continuously co-measured (Karnosky et al., 2003a), it might be possible to actually develop a model that would predict growth. Accordingly, we have used 5 years of co-measured response and predictor data from the world's largest free-air O_3 experiment (Aspen FACE) to test this hypothesis. In particular, we have used the North American air quality standard as the O_3 predictor so as to increase utility of the model and potential for scaling up (Karnosky et al., 2005).

2. Methods

2.1. The Aspen FACE Experiment

The Aspen Free Air Carbon Dioxide Enrichment (FACE) Experiment is located near Rhinelander (45°06'N; 89°07'W; 490 m asl; http://aspenface.mtu.edu) in northern Wisconsin, USA. The 32-ha site contains 12 30-m dia. FACE rings in a randomized block design, with one ring for each of four treatments (control, CO_2, O_3, CO_2+O_3) per block. Complete detail on site physical/biological characterization, experimental design, species (genotype) planting and micrometeorological measurement is available (Dickson et al., 2000; Karnosky et al., 2003b). For this study, 5 years (1999–2003) of co-measured growth response and predictor data from control and elevated O_3 rings were used. During the study period, elevated O_3 was maintained at 1.40 times to 1.34 times ambient delivered with a diurnal surface exposure profile as described in Karnosky et al. (2005).

2.2 Response and predictor indicators

The growth endpoint used in the study was individual tree diameter converted to mean basal area (m^2) for five trembling aspen (*Populus tremuloides* Michx.) clones of known and widely varying sensitivity to O_3 and for white birch (*Betula papyrifera* Marsh.). Tree diameters were measured annually at the end of the growing season in the core areas of the mixed genotype aspen ring half and the mixed species aspen/birch quarter ring. Predictor variables used in the study included: seasonal 4th highest daily max. 8-hour average O_3 concentration; seasonal growing degree days (temperature to base 10°C); average seasonal wind speed; seasonal accumulated photosynthetically active radiation (PAR); average seasonal relative humidity (RH) (0900h); seasonal accumulated precipitation; and seasonal average soil moisture content. Hourly average O_3 concentrations were measured at the centre of O_3 rings and at the ambient O_3 monitor (applied to control rings; EPAAIRS ID 550850004420101). Soil moisture content was measured biweekly within the rings. Other predictors were measured at 10 m on the meteorological tower or near its base (precipitation).

2.3 Statistical analysis

We built 10 cases [5 years x two FACE rings (one control, one elevated O_3)] and eventually 30 cases [5 years x six FACE rings (three controls, three elevated O_3)]. *Here, we report only on results from the 10-case analysis, with particular emphasis on comparative evaluation of performance of the five O_3 indices.* Pearson correlation was used initially to test for relationships among O_3 indices examined. Best subsets regression technique was used to determine O_3 and meteorological predictor goodness of fit for aspen clone and birch mean basal area growth. Polynomial cubic regression was employed to determine shape of the dose response curve for O_3 predictor index. Finally, Monte Carlo techniques were used to develop models for aspen clone and birch response based on thousands of predictor combination scenarios

3. Results

3.1 Ozone predictor ranges

For the growing season fumigation periods maximum hourly O_3 concentrations in the O_3 treatment ranged between 80–98 ppb (Table 1). Seasonal 4th highest daily max. 8-hour average O_3 concentration ranged from 78 (2000) to 94 (1999). The ranges in accumulated AOT40 for the May–October periods (0700–2100 h) and SUM60 are also listed in Table 1.

Table 1. Ozone exposures during 1999–2003 in two Aspen FACE rings

Treatment	1-hour max (ppb)	4th highest** (ppb)	AOT40 (ppbh)	SUM60 (ppbh)
Control	75 – 93*	65 - 82	4800 - 7700	200 - 500
Elevated O_3	80 – 98	78 - 94	23600 - 35300	8400 - 16600

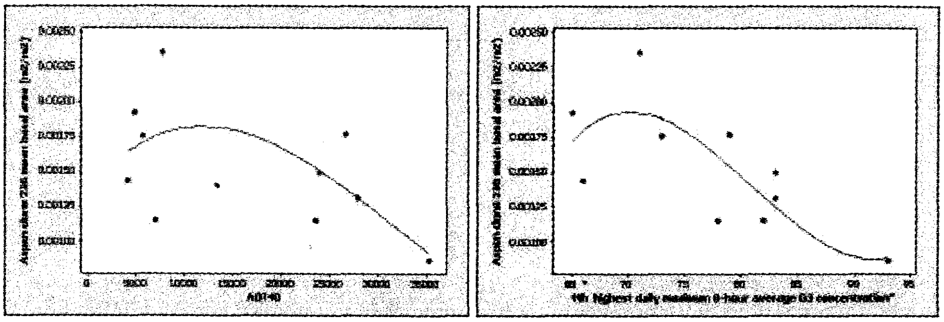
* Data available at http://oaspub.epa.gov/airsdata/
** Seasonal 4th highest daily max. 8-hour average O_3 concentration

3.2 Efficacy of O_3 indices as predictors of growth response

The five indices (4th highest, AOT40, SUM60, SUM00, max 1-hour) investigated were all significantly inter-correlated to varying degrees. Highest degree of Pearson correlation was between AOT40 and SUM60 or SUM00 (P = 0.000). Best subsets regression techniques were used to evaluate goodness of fit between aspen clone (5) and white birch basal area growth vs. fourth highest, AOT40, SUM60, SUM00 and max. 1-hour O_3 indices. For white birch and the five aspen clones, 4th highest daily maximum 8-hour average O_3 concentration provided the best fit with highest r^2 (adj). In fact, only 4th highest and SUM60 were determined to be good independent single predictors of basal area growth over the 5-year period. For instance, with aspen clone 216, basal area growth was considerably more dependent on 4th highest O_3 [r^2 (adj.) 41.0%] than upon SUM60 [r^2 (adj.) 30.7%]. No other indices emerged in the analysis as being good predictors by themselves.

The intrinsic relationship between O_3 and tree growth is, of course, non-linear. This can be observed from the plots of polynomial cubic regression of tree growth we used to investigate relative performance of each index as a single predictor of aspen and birch basal area growth in one control, and one elevated O_3 rings. Here, we present aspen clone 216 (Figure 1) as a model. It is responsive to O_3 and considered to be of medium sensitivity (Karnosky et al., 2003b).

Figure 1. Polynomial cubic regression of mean basal area growth for aspen clone 216 from one Control and one elevated Aspen FACE O_3 ring.



Polynomial cubic regression analysis produced regression equations of the form: $Y = a + bX + cX^2 + dX^3$, where Y is mean basal area growth (m^2), and X = 4th highest daily 8-hour maximum average O_3 concentration (ppb). Basal area growth demonstrated lower dose stimulation followed by higher dose inhibition when regressed on 4th highest and AOT40. A similar response surface was not observed with SUM06, SUM00 or max.1-hour O_3. Ozone appears to be detrimental to aspen clone 216 basal area growth between 68–70 ppb (4th highest daily max. 8-hour average O_3) or between approximately 11000–12000 AOT 40 ppb O_3 (Figure 1).

As can be seen in Table 2 below, basal area growth in aspen clone 216 was clearly more dependent upon 4th highest daily maximum 8-hour average O_3 concentration singly, than upon SUM60, SUM00, AOT40 and certainly maximum 1-hour. The fact that the relationships were not statistically significant (Table 2) strongly indicates that 4th highest, or any other of the five indices based on a cubic polynomial model, ***cannot by themselves be used to predict*** aspen or birch growth. Nevertheless, it is revealing that with our data, the North American standard form appears to outperform AOT40, SUM06, SUM00 and max 1-hour.

Table 2. Comparative efficacy of various indices as single predictors of aspen clone 216 growth response in cubic regression models.

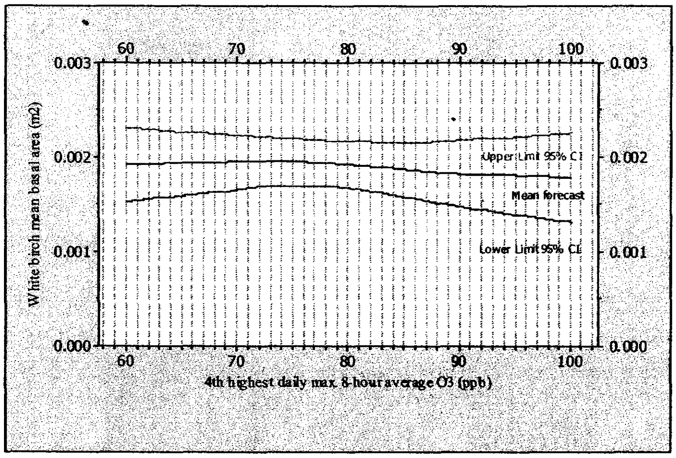
O_3 index	r^2	r^2 (adj.)	P
4th highest	58.2	37.4	0.132
AOT40	36.3	4.5	0.406
SUM60	43.5	15.2	0.299
SUM00	38.9,	8.4	0.365
Max 1-hour	23.2	0.0	0.636

3.3 Dose response functions

Best subsets regression performed on the 10 cases under consideration showed the three best predictors [r^2 (adj.) > 78%; $P < 0.007$] of aspen and birch basal area growth to be 4th highest daily maximum 8-hour average O_3 concentration, growing degree days and wind speed. Multiple linear regression equations took the form: mean basal area = a – b (4th highest daily maximum 8-hour average O_3 concentration ppb) + c (growing degree days; ^{0}C to base 10°) – d (wind speed; m s^{-1}). Preliminary work with the full 30 cases is underway to produce dose response functions for the five aspen clones. These appear at this stage to predict a range of effect from a small stimulation in basal area growth for the most tolerant clone, to about 20% growth inhibition for the most sensitive clone across a range of 4th highest daily maximum daily 8-hour average O_3 concentrations measured over much of the 26 million-ha natural range for aspen in North America. White birch was less responsive within the 65–90 ppb O_3 range (Table 1), as can be seen the dose response model (Figure 2) developed using 30 cases. The model predicts no change in mean basal area from 60–65 ppb O_3;

slight (~+2.5%) stimulation from 65–70 ppb; a decrease (~-2.5%) to 75 ppb O_3 and, a further ~2.5 % decrease at 80 ppb O_3. The confidence bands are *not parallel,* signifying widening of the corresponding confidence intervals.

Figure 2. Dose response curve for white birch mean basal area growth and O_3 exposure calculated using the North American standard



4. Discussion

It is somewhat surprising that there was a high degree of correlation at Aspen FACE during 1999–2003 between the 4th highest daily maximum 8-hour average O_3 concentration and the two cumulative indices AOT40 and SUM60. This may be due in part to the fact that northern Wisconsin has relatively low background O_3 levels and the performance of the FACE O_3 delivery system was very good when adding 1.34–1.4 x more O_3 to the background diurnal profile, despite year-to-year variation in meteorology.

It is interesting that, at least for the data considered here, the 4th highest daily maximum 8-hour average O_3 concentration was determined to be the best single predictor for basal area growth in aspen and birch. As indicated earlier, the North American O_3 air quality standard is promulgated to protect human health. The North American standard was a better single predictor of basal area growth in some clones than in others. Three of the clones investigated at Aspen FACE were initially selected from over 200 surveyed across the US (Berrang et al., 1986). Aspen clone 8L [r^2 (adj.) 7.1%] is highly O_3 tolerant and can be slightly stimulated by O_3. In contrast, aspen clone 216 [r^2 (adj.) 41%] has medium or greater tolerance to O_3 (Karnosky et al., 2003b). White birch at Aspen FACE has been shown to be relatively O_3 tolerant (Karnosky et al., 2003b) and appears to behave in a manner not unlike aspen clone 8L.

We are cognizant of the fact that tree growth is a non-linear process. However, for utility and use by regulators within the North American air quality context, a dose response function must be not only scientifically defensible (high goodness of fit, statistical significance, biological validity), but also simple to use. Hence, our dose response functions were built using linear regression techniques. In the end, simplicity was achieved with only a very slight loss [about 2% r^2 (adj.)] in predictive power. Of course, the accuracy of the forecast will depend on the O_3 ozone concentration. It is apparent that the accuracy of the forecast as measured by its standard error is highest in the middle of the graph (average O_3) and decreases toward the outside (low or high O_3). This is an intrinsic attribute of regression forecasts.

The work described here was based on examination of only 10 cases from Aspen FACE. Although not statistically very good, it is in broad agreement with our preliminary, unpublished work with 30 cases. The work described here, and that currently underway, demonstrates the potential scientific and practical utility of a simple predictive model incorporating the North American ozone air quality standard metric and additional meteorological variables important in O_3 flux as earlier postulated by Krupa et al. (2003).

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