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Incidence of Ozone Injury on Hybrid Poplar Trees in Southwestern Pennsylvania USA: A 26-Year Field Study

Research Article

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Abstract

During 1991 to 2016, we evaluated the annual incidence (percentage) of hybrid poplar trees exhibiting ozone (O_3)-induced leaf injury (stipple) within 15 planted field-study plots in southwestern Pennsylvania, USA. Incidence of stippled poplars decreased from a mean of 3.84% in 1991 to 0.00% in 2016. Mean annual 8-hr ambient O_3 concentrations, downloaded from a U.S. EPA monitoring site located ca 60 km west (upwind) from the closest study plot, decreased from 96 ppb in 1991 to 67 ppb in 2016. Regression analysis revealed that during the 26-year period, the annual incidence of poplar trees exhibiting ozone-induced leaf stipple was significantly and linearly related to the mean annual O_3 concentration.

Keywords: Air pollution; Ozone; O_3; Hybrid poplar trees; Leaf stipple

Introduction

Tropospheric ozone (O_3)

Tropospheric ozone (O_3) is the most important phytotoxic (plant damaging) air pollutant in the USA [1,2]. Ozone is a secondary air pollutant formed by photochemical reactions between Oxides of Nitrogen (NO_x) and Volatile Organic Compounds (VOCs), two precursors to O_3 formation [1,3,4]. Rural Pennsylvania (PA, USA) contains phytotoxic levels of ambient O_3 [2,5,6], especially in areas that experience long-range transport of NO_x and VOCs within slow-moving, stagnant, high-pressure systems [7]. Predominantly east-bound weather systems traverse the industrial Ohio River Valley on the western border of PA and the Pittsburgh industrial areas, collecting precursors to O_3 formation before entering our study area in southwestern PA. Elevated levels of ambient O_3 in the study area usually begin in May, increase through the summer, and often peak in August. Diurnal patterns often reflect greater ozone concentrations in mid-afternoon when O_3-forming reactions are driven by incoming solar radiation, and lowest O_3 levels generally occur after sunset, when O_3 is continuously converted back to NO_2 and O_2 in the presence of NO [1,4,8].

Ozone injury to vegetation

The importance of O_3 as a significant phytotoxic air pollutant in the USA was first reported in the USA by Richards et al. in 1958 [9]. They had previously observed O_3-induced leaf injury on wild and cultivated grapes (*Vitis* spp.) as early as 1954 in the Los Angeles, CA air-basin. They described O_3-induced leaf symptoms as "stipple," which were comprised of groups of dark brown-to-black, leaf palisade-mesophyll cells visible through the hyaline adaxial epidermis

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and overlying cuticle. Stipple on many species of broadleaved plants was later shown to be indicative of phytotoxic concentrations of ambient O_3, which could be used to identify O_3-sensitive bioindicator plants [2,10,11]. Early researchers observed that the incidence and severity of O_3-induced stipple varied among individuals within an open-pollinated species depended on their parentage [12]. However, variability could be minimized by using asexual, clonally propagated (e.g., from cuttings) bio-indicator plants [Davis, personal observations].

On 1 October 2015, the U.S. Environmental Protection Agency (EPA) enacted a more stringent National Ambient Air Quality Standard (NAAQS) for ground-level O_3 [13]. The new standard was based on the 4th highest daily maximum O_3 concentration, averaged across 3 consecutive years for an averaging time of 8 hrs [14]. If that value exceeded 70 ppb, the relevant area was considered to be in nonattainment of the standard. Southwestern PA, including our study area, was in attainment of the new NAAQS for 2016 to 2018, the 3 most recent years for which EPA O_3 data were available at time of this writing (https://www3.epa.gov/airquality/greenbook/map8hr_2015.html, accessed 24 September 2019).

Objectives

The general objective of this study was to evaluate temporal and spatial patterns of incidence (percentage) of planted hybrid poplar trees that exhibited O_3-induced stipple during 1991 to 2016 on study plots in southwestern PA. The specific objective was to determine if annual ambient ozone levels were statistically related to the annual incidence of ozone-induced poplar stipple during the 26-year period.

Material and Methods

Ambient ozone concentrations

Annual mean 8-hr ambient O_3 concentrations (ppb) for 1991 to 2016 were downloaded from EPA O_3 monitoring site #42-003-00008 (40°27'55"N, 79°57'38"W), located ~40 km westward and upwind from the study area.

Study area

The study area is located in a rural portion of the Appalachian Plateau Physiographic Province in southwestern PA (Figure 1), as described by McClenahen et al. [15]. The area has a rolling dissected topography with ridges oriented in a southwest-northeast direction and elevations ranging from ~400 - 800 m. The climate is continental, average annual precipitation is ~100 cm, and prevailing winds are from the west. Although the study area is mainly rural, it contains scattered industries and is located downwind from the Pittsburgh and the Ohio River Valley industrial areas, which are major sources of precursors to O_3 formation. Johnstown, which has a 100-year history of air pollutant emissions from steel mills and coke works [16], lies slightly downwind from the southeastern edge of the study area and may be a source of O_3 and precursors during winds from the southeast.

Study plots

In 1964, Hutnik et al. established a network of ecological plots in former agricultural fields within the study area to study effects of sulfur and SO_2 on coniferous plants [17]. However, during the late 1960s and early 1970s, air pollution effects research in PA shifted emphasis from primary pollutants such as SO_2, often localized near point sources, to the widespread secondary air pollutant O_3 [Davis, personal observations]. Therefore during 1972 to 1976, Hutnik and colleagues established 20 rooted cuttings of an O_3-sensitive hybrid poplar clone (*Populus maximowizii x trichocarpa* USDA Forest Service Northeastern Forest Experiment Station Clone NE 388) on each of 22 50x50 m plots as bioindicators of phytotoxic levels of ambient O_3 [18]. During 1981 to 1990, the years with the most complete datasets at the time, the incidence of O_3 injury on the poplar trees was significantly (P = 0.05) correlated with the number of days having hourly O_3 concentrations > 40 ppb [18]. By 1991 several original plots had been lost due to change of land ownership and various land-use changes. Therefore, we selected 15 of the remaining intact study plots for use in this 26-year study beginning in 1991 (Figure 1). Large poplars were removed to minimize plot shading and were replaced with new rooted cuttings of the same clone; data were not taken on the new cuttings until 1 year after establishment.

Evaluation of visible ozone injury

Beginning in 1991, each poplar tree on each plot was evaluated for presence or absence of visible O_3-induced leaf stipple (Figure 2), which was shown to be caused by O_3 in controlled studies [18]. Symptom evaluations were conducted in early to mid-August, usually the time of greatest O_3 injury on native broadleaved plants in the study area [5,7,19]. Stipple on each tree was classified as present or absent, and incidence (percentage) of poplar trees exhibiting stipple/plot/year calculated until the study was terminated in 2016.

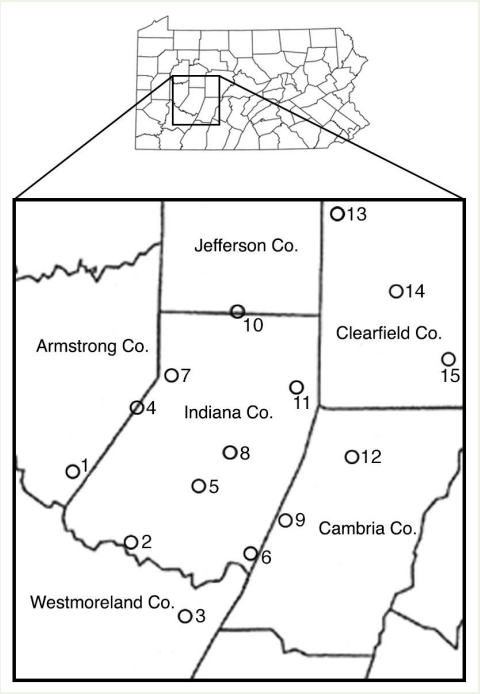

Figure 1: Location of study area in southwestern PA, USA. Open circles with numbers denote the 15 study plots. Figure adapted from Hutnik et al. [17].

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Figure 2: Severe adaxial (upper) leaf surface stipple induced by ambient O_3 on hybrid poplar trees in the study area. (Photograph by DD Davis).

Statistical analyses

Polynomial regression was performed with SAS's PROC REG (SAS for Linear Models, 4th Ed.) to evaluate the relationship between O_3-induced leaf injury and mean annual ambient ozone concentration. However, only the linear term was significant and residual plots indicated the quadratic term did not improve the model. Therefore, linear models were fit in order to model changes in O_3 ambient concentrations and leaf injury over the 26-year study period.

Results and Discussion

Regarding general temporal patterns, ambient O_3 data downloaded from the EPA monitoring site revealed that the annual mean 8-hr O_3 concentration decreased from 96 ppb in 1991 to 67 ppb in 2016, a 30% decrease (Figure 3). Mean annual percentage of hybrid poplar trees exhibiting O_3-induced stipple decreased from 3.84% in 1991 to 0.00% in 2016, the last year of the study (Table 1). For the entire 26-year period, the mean annual ambient O_3 concentrations and mean annual percentage of O_3 injury on poplars were significantly and positively correlated in a linear manner ($n = 26$, $R^2 = 0.39$, $P = 0.001$). The complete lack of leaf stipple in 2016 was possibly due to ambient O_3 levels being below a general level needed to induce O_3 injury, or to environmental conditions that were not conducive to O_3 uptake and subsequent development of foliar injury.

The temporal pattern of O_3 injury incidence peaked in 1998. However, this peak did not appear to be strongly related to a peak in ambient O_3 concentration in (Figure 3). Therefore, the 1998 peak may have been influenced by environmental factors such as ideal soil moisture levels that were conducive to maximum O_3 uptake that occurred concurrently with environmental conditions conducive for maximum foliar injury. Foliar O_3 injury precipitously decreased in 1999, but the decline did not appear related to a similar decline level of ambient O_3 (Figure 3).

However, injury-threshold values are only general estimates [20]. Onset of O_3-induced foliar injury can be influenced by multiple interacting factors, including genetic (inherent species O_3 sensitivity or tolerance), physiologic (detoxification capacity, defense mechanisms), physiographic (elevation), environmental (drought), seasonal, and others. These confounding factors and their interactions make it difficult to determine meaningful O_3 injury threshold values [20].

Relatedly, Smith et al. reported a similar temporal trend in O_3 injury in a large study involving the incidence of O_3-induced stipple on milkweed bioindicator plants (n = 65,448) in the northeastern USA from 1994 to 2010 [21]. Similar to our findings, they also reported a peak of O_3 injury in 1998 followed by low stipple levels in 1999 that they related to a widespread drought that occurred in 1999 within northeastern USA. This drought also encompassed our study area, as verified by the Palmer Drought Severity Index for southwestern PA (Figure 4) [22]. Figure 4 also illustrates that two severe drought

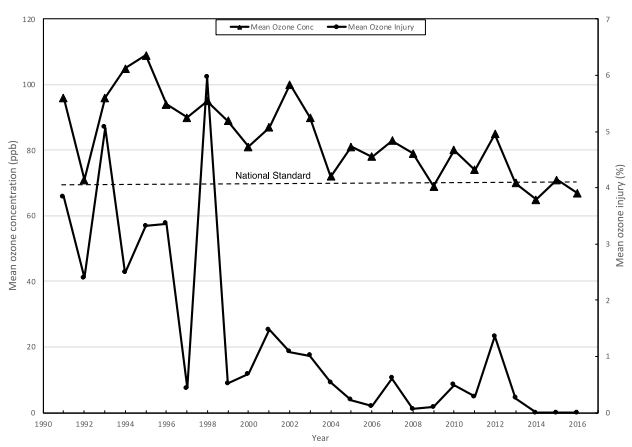

Figure 3: Top line. Mean annual 8-hr ambient ozone concentrations (ppb) downloaded from an EPA O_3 monitoring site located immediately west (upwind) of the study area. Horizontal dashed line represents the ozone concentration (70 ppb) used in calculating the current USA NAAQS for O_3 . Bottom line. Mean incidence (%) of poplar trees exhibiting O_3 -induced leaf injury.

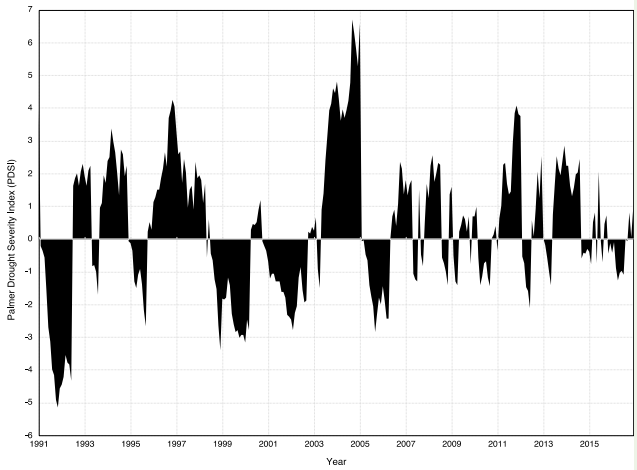

Figure 4: Palmer Drought Severity Index (PDSI) for southwestern Pennsylvania during 1991 to 2016. The horizontal line at a PDSI value of "0.0" on the y-axis reflects normal moisture levels. Areas above the line generally represent a gradient of adequate to surplus moisture for normal plant functioning, whereas areas below the line represent a gradient of adequate moisture to water stress. A drought severity index of -3 represents severe drought that may induce stomatal closure and reduce O_3 uptake by vegetation.

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Table 1: Percentage of ozone-induced stipple on leaves of hybrid poplars on study during plots 1991-2016.

Plot	Year																									
ID[v]	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
1	0.25	0	2.45	0.47	2.31	3.2	0.5	2	0.27	1	1.11	1.22	0.3	0.09	0	0	0.14	0	0	0	0	0.19	0	x	x	0
2	24.78	7.94	26.67	14.26	26.68	17.44	2.68	35.6	0.7	2.53	6.32	2.11	5.42	0.63	0	0.05	0	0	0	5.21	2	5	2.09			0
3	x,y																									
4	0	0	1.05	0	0.25	0.26	0	9	0	0	1.4	0.63	0.28	0	0	0	0	0	0	0	0	0.28	0			0
5	12	5.38	3.21	1.47	1.24	7.61	0.33	3.31	0.39	0.47	2.68	1.25		0	0	0	0.75	0.69	0	0	0.76	0.29	0			0
6	0.21	0.06	2.16	0	0.78	2.39	0	8.87	1.74	0.33	0.32	0	0.12	0	0	0	0	0	0	0	0	0.28	0			0
7	0	0	0.31	0.45	0	1.79	0	1.93	0	0	0	0		0	0	0	0	0	0	0.12	0.45	0.14	0			0
8	5.76	0	7.44	5.24	0.75	1.44	0	12.93	0.06	0.13	0.5	0.73			0.5	0	2.38	0	0	0	0	0.27	0			0
9	7.53	13.94	18.94	6.58	7.31	5.18	0.82	6.04	1.04	0.68	6.45	3.13	1.33	5.06	1.29	0.15	1.23	0	1.15	0	0.35	10.24	0.86			0
10	0	0	0.15	0.31	0	0.79	0	0.33	0.14	0.12	0	0	0.04	0.13	0				0	0	0	0.08	0			0
11	1.79	1.56	3.61	0.41	0.5	1.38	0.13	1.44	0.25	0.45	0.18	3.95	0.47	0.8	0.57	0.53	2.05	0.06	0.05	0.58	0	0.29	0			0
12	1.48	3.81	3.45	1.22	5.86	1.84	0.38	0.65	2.36	2.33	1.39	1.83	1.82	0	0.8	0		0	0.17	0.48	0	0.91	0			0
13	0	0	1.36	0.21	0	1.29	0.41	0.69	0	0	0	0		0.13	0	0	0.54	0	0	0	0.21	0.05	0			0
14	0	0	0.12	1.82	0.12	1.94	0.18	0	0		0	0.22	0.33	0	0	0.78	0.22	0	0	0	0	0.36	0.62			0
15	0	0.91	0.15	2.38	0.65	0.53	0.59	0.65	0.24	0.88	0.24	0.09	0.04	0.07	0	0	0	0.09	0	0.52	0.16	0.62	0			0
Mean	3.84	2.4	5.08	2.49	3.32	3.36	0.43	5.96	0.51	0.69	1.47	1.08	1.02	0.53	0.23	0.12	0.61	0.06	0.1	0.49	0.28	1.36	0.26	0.08[z]	0.03[z]	0

[v]See Figure 1; [x]Blank spaces indicate no data; [y]Plot 3 discontinued in 1994; [z]Means determined prior to loss of original data

periods occurred in southwestern PA during the period from 1999 to 2003. During this time interval, the drought likely caused soil moisture stress, resulting in closed stomata and reduced O_3 uptake, which in turn could reduce O_3 injury on sensitive bioindicators [21,23]. The low level of O_3-injury on poplars then persisted through 2016, except for small peaks of injury in 2001 and 2012 (Table 1 and Figure 3). These small peaks may have been partially related to subtle changes in O_3 concentrations in combination with subtle changes in soil moisture (Figure 3). Interestingly, the similar temporal patterns in O_3 injury between our study involving poplars and that of Smith et al. involving milkweeds, suggest similar environmental factors for the two species that influenced the percentage of O_3 injury [21]. Such common factors may influence O_3 injury in other various plant species [21,23].

Regarding spatial patterns, during 1991 - 2003 and 2010 - 2013, mean O_3-induced leaf symptoms on poplars appeared to be slightly greater on plots in the west-southwest (generally upwind) portion of the study area and becoming less severe with distance downwind (to the northeast) (Figure 1 and Table 1). This upwind-to-downwind decreasing pattern is likely attributable, at least partially, to O_3 precursors (NO_x and VOCs) originating from industries in southwestern PA and the Ohio River Valley. However, during the later time period from 2014 to 2016, O_3 injury was minimal and therefore spatial patterns could not be discerned (Table 1 and Figure 3). In 2016. for the first time since the study began, O_3 injury was not observed on ozone-sensitive hybrid poplar.

Conclusion

The incidence of O_3-induced stipple on hybrid poplar trees on field-study plots in southwestern PA decreased from a mean of 3.4% in 1991 to 0.00% in 2016. Mean annual 8-hr ambient O_3 concentrations, downloaded from a nearby U.S. EPA monitoring site likewise decreased during the 26-year study. During 1991 to 2016, the mean annual incidence of poplars exhibiting stipple induced by ambient ozone was significantly ($P = 0.001$) correlated with the mean annual ozone concentration.

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