Monitoring Air Pollution for Its Potential Impact on Agricultural Crops in SW Indiana

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Introduction

During recent years severe foliar injury has been observed on the commercial muskmelon and watermelon crops of southwestern Indiana. The injury resulted in a significant loss of marketable fruit from the region. Air pollution was suspected of causing part of the damage since some of the visible symptoms resembled ozone and sulfur dioxide induced injury found on other plant species (8,9).

Ozone (O_3), sulfur dioxide (SO_2), and nitrous oxides (NO_x) are the most prevalent gaseous air pollutants. Ozone has been reported to be the most injurious air pollutant to crop plants nationwide with damage resulting with and without visible symptoms (13). A recent study by Loehman and Wilkinson (11) predicted that significant losses are occurring in Indiana due to O_3 stress. Ozone, produced during the daylight hours, is generated when sunlight reacts with NO_x and hydrocarbons released into the atmosphere as by-products of the combustion of fossil fuels (13). A photolytic reaction reduces NO_2, producing an oxygen atom which spontaneously reacts with molecular oxygen, forming O_3. Sulfur dioxide is released directly into the atmosphere as a by-product from the combustion of fossil fuel containing sulfur.

Indiana is one of the leading states in SO_2 emissions, releasing >500,000 tons of SO_2 annually into the atmosphere. Some of Indiana's largest industrial sources of SO_2 are located in SW Indiana, with several in the vicinity of the major melon growing areas in Knox, Sullivan, and Gibson counties (Table 1). The same stationary sources that burn coal, oil, natural gas or other fuels releasing SO_2, can also contribute to the formation of NO_x, the precursor to O_3. Regional climatological conditions result in prevailing winds from the west, southwest, south and southeast during the summer

Table 1. The Major Sources of Sulfur Dioxide Emissions in Indiana.[1]

Plant	SO_2 tons/year*	Location
PSI•	291,724	Near Princeton, Gibson Co.
IKEC Clifty Falls	227,559	Madison, Jefferson Co.
Alcoa Generating Corp.	145,783	Newburgh, Warrick Co.
PSI Cayuga	114,213	Cayuga, Vermillion Co.
IPL Petersburg	100,539	Petersburg, Pike Co.
I&M Tanners Creek	76,545	Lawrenceburg, Dearborn Co.
PSI Gallagher	73,085	New Albany, Floyd Co.
I&M Breed	69,253	Fairbanks, Sullivan Co.
SIGECO Culley	67,132	Yankeetown, Warrick Co.
IPL Stout	60,120	Indianapolis, Marion Co.
NIPSCO Bailly	57,867	Near Chesterton, Porter Co.
NIPSCO Michigan City	55,136	Michigan City, LaPorte Co.
PSI Wabash River	48,043	Terre Haute, Vigo Co.
Hoosier Ratts	36,163	Petersburg, Pike Co.
IPL Pritchard	24,092	Centerton, Morgan Co.

[1]Data provided by the Indiana State Board of Health, Indianapolis, IN. Based on 1983 EIS Update (1983 Emissions).

TABLE 2. Percentage of wind rose for each wind direction from June, July, and August, 1965-1974 at Evansville, IN.

	June	July	August	Avg.	Quadrant Avg.
Calm	11.2	11.7	13.6	12.2	
N	6.2	7.1	8.8	7.4	
NNE	2.3	2.9	3.0	2.7	
NE	3.9	4.0	4.7	4.2	
ENE	4.0	4.1	5.1	4.4	19
E	5.2	5.9	7.0	6.0	
ESE	2.9	3.4	2.9	3.0	
SE	4.7	3.2	4.7	4.2	
SSE	4.9	3.5	3.2	3.9	17
S	12.1	8.3	7.5	9.3	
SSW	6.5	5.5	4.7	5.6	
SW	10.1	8.5	8.1	8.9	
WSW	6.2	6.9	5.1	6.1	30
W	4.6	5.9	4.2	4.9	
WNW	5.1	5.6	3.9	4.8	
NW	5.8	7.3	7.1	6.7	
NNW	4.3	6.1	6.3	5.6	22

months (Table 2), which may also transport potential air pollutants into SW Indiana from such urbanized centers as Louisville, Kentucky and St. Louis, Missouri.

Seasonal weather conditions reveal that 1984 was slightly drier than normal with near normal temperatures, and 1985 was a cooler than normal season with slightly above normal rainfall (Table 3). These seasonal weather summaries are based on monthly data from 13 NOAA Climatological "A" network stations in the 12 southwestern counties plus the NOAA-NWS-WSO at Evansville, Indiana for May, June, July, and August.

TABLE 3. Climatological data during the 1984-85 growing season in SW Indiana.[1]

1984

	May	June	July	August
Air Temperature	61.8°F	77.2°F	76.0°F	
Normal	64.9	73.6	77.1	75.4
Departure	− 3.1	+ 3.6	+ 0.6	
Precipitation	4.30″	1.42″	3.18″	2.34″
Normal	4.41	3.99	4.54	3.57
Departure	− 0.05	− 2.57	− 1.26	1.23

1985

	May	June	July	August
Air Temperature	66.1°F	71.8°F	76.7°F	73.8°F
Normal	64.9	73.6	77.1	75.4
Departure	+ 1.2	− 1.8	− 0.4	− 1.6
Precipitation	4.83″	5.02″	2.36″	5.12″
Normal	4.41	3.99	4.54	3.57
Departure	+ 0.42	+ 1.03	− 2.08	+ 1.55

[1]The climate data is computed from the following stations: Crane Naval Depot, Dubois (SIPAC), Elliston, Evansville AP, Evansville (City), Freelandville, Jasper, Mt. Vernon, Princeton, Shoals, Spurgeon, St. Meinard, Vincennes, Washington.

A research study was designed to determine the relationship of air pollution and the occurrence of melon injury, by first quantifying the presence and geographical extent of specific air pollutants in the affected region. This paper describes the monitoring system established in SW Indiana to determine the ambient rural concentrations of O_3, SO_2, and precipitation composition. The actual pollutant levels and the pH of the precipitation in SW Indiana were monitored as an indicator of the presence of air-borne pollutants that affect the chemistry of precipitation. A biomonitoring approach using plant cultivators known to exhibit characteristic foliar injury or abnormal growth when exposed to air pollutants was also used to characterize the geographical area in which air pollution was present. The use of sensitive plants or plant bioindicators for determining the presence of air pollution has been well documented and previously described (3,4,5,6,12).

Site Selection

Two monitoring sites were selected to measure the rural ambient concentrations of O_3 and SO_2 during the 1984 and 1985 growing seasons. Site selection was based upon predicted air pollution levels and regional meteorological conditions. The first site (see Fig. 1, site #11) was in a melon field where severe foliar damage on melons had been observed in previous years. This site was located 1 mile east of SR 41 on Old Decker Road in Decker, downwind from stationary sources of SO_2 and predicted to receive the potential maximum air pollution, with respect to SO_2, from local point sources such as the Gibson Power Plant. Local growers confirmed that the melon crops in this area sustained considerable damage yearly since the phytotoxicity symptoms were first observed. The second site located 24 km north of site #11, at the Southwest Purdue Agricultural Research Center (SWPAC), approximately 7 km north of Vincennes, was expected to receive less air pollution because of its location relative to pollutant sources and since melon damage had been observed to a lesser extent.

Four sites were selected for bulk precipitation collection in or adjacent to melon producing fields. Two of these sites also have wet-dry precipitation collectors and are located with the O_3 and SO_2 monitoring sites.

Bioindicator monitoring sites were established in 13 commercial and experimental melon fields in a multi-county area (Figure 1). Sites were selected based on their location relative to known industrial sources of SO_2. These sites were located in the major areas of melon production. To correlate injury on bioindicators with actual ambient air pollution levels, two of the bioindicator sites (Decker, site #11 and SWPAC, site #5) were located at the same site where air quality was monitored (Figure 1).

Materials and Methods

Ambient O_3 concentrations were measured continuously with a Bendix 8022 chemiluminescent and a Dasibi ultraviolet (UV) photometric analyzer at the SWPAC and Decker sites, respectively. Ambient SO_2 concentrations were measured continuously by UV stimulated fluorescence and pulsed fluorescence at the SWPAC and Decker sites, respectively. All recorded data was quality assured by the Indiana State Board of Health, Air Pollution Division.

The pH of the precipitation was collected by two methods. Wet-only precipitation collections were made using an aerochemetrics wet-dry collector following the National Atmospheric Deposition Network (NADP) procedures (15) at SWPAC and a similar collector with similar procedures except collections were twice weekly at the Decker site. The values presented here are from the wet-side collections only. At both locations the dry-side collector was removed and rinsed with a 250 ml aliquot of distilled water. The rinse water was then analyzed following the same procedures used for the

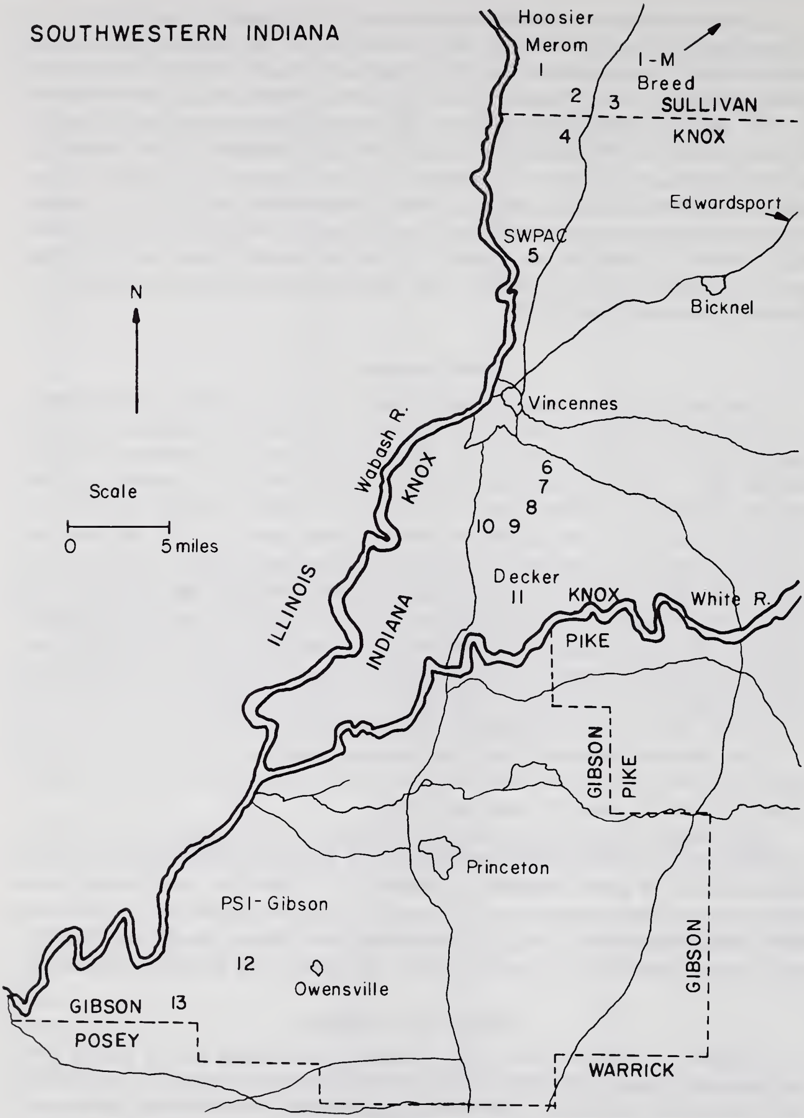

FIGURE 1. Map of study area. Numbers indicate bioindicator sites in 1984.

precipitation samples. Bulk precipitation was collected twice weekly at both locations using 6 inch (15.24 cm) diameter polypropylene funnels attached to 1 liter bottles. There were 3 replications at each site. All precipitation samples were analyzed for pH and conductivity and weighed upon arrival at the laboratory. The samples from the NADP collector at SWPAC were submitted directly to the national central analytical laboratory for analysis after pH and conductivity were recorded at the site.

Bioindicator plants were grown in melon fields and visually rated for pollution-like symptoms. Plant species selected for use as indicators of ambient air pollution and used successfully in similar studies (3,4,5,6) included: tobacco (cvs. Bel W3 and Bel B); beans (Bush Blue Lake [BBL] 290); Pinto I-11; Oregon State University [OSU] 1604; soybeans, cv. Cutler); and Early Summer Yellow Crookneck Squash. The soybeans and squash are sensitive indicators of SO_2, while the remaining species are O_3-sensitive (4,8,9). In 1984, at each of 13 sites (Figure 1), seeds of [BBL] 290, OSU 1604, soybeans and squash were sown in a randomized complete block design with 2 to 3 replications at each site. At the Decker and SWPAC field sites, Pinto I-11 and tobacco were also evaluated. Tobacco was transplanted to the field at the same time all other plants were seeded. Plant spacings differed for each species, but rows were 1 m apart, with a minimum of 7 plants per plot. Standard planting and cultural practices were followed throughout the growing season (10). All sites were planted within one week of June 19, 1984. Plants were irrigated for 3 to 4 weeks to facilitate plant emergence and stand establishment. Field sites were visited weekly for maintenance of plots and to record plant injury based upon a visual rating system of 0-10, 0 indicating all leaf area injured and 10, absence of leaf injury, respectively. Foliar injury was recorded starting 2 weeks after plant emergence from the soil and included only injury typical of that induced by air pollution. Final injury ratings for bioindicators were made during the last week of August (the approximate end of the melon growing season). The appearance of pollution-like foliar systems was used as an indication of the presence of air pollution. In 1985, five sites were used in the bioindicator study as outlined above.

Soil samples were taken 3 times during the growing season to determine if foliar injury could have been influenced by low pH soil. Recently, acid soil conditions have been reported to induce manganese toxicity and/or magnesium deficiency in melons in this region (17). Plant tissues were also sampled periodically for nutrient analyses.

Results

Diurnal variation of mean hourly ambient O_3 concentrations over the entire 1984 and 1985 growing seasons showed that O_3 levels were in excess of 0.050 ppm daily for 10 hours in 1984 and 7 hours in 1985 (Figure 2). In 1984, average O_3 concentrations exceeded 0.070 ppm for several hours daily. Ambient O_3 concentrations for 1984 are shown on a monthly basis in Figure 3. Ozone concentrations were higher in July than in May, June, or August (which had similar O_3 levels). Percentage of total hours with specific hourly average O_3 concentrations (Table 4) illustrate that in 1985, O_3 concentrations were higher at the Decker than at the SWPAC site.

TABLE 4. Percentage of total hours with hourly average ozone concentrations in given ranges during the 1984 and 1985 experimental growing seasons for melons in southwestern Indiana.

Oxidant Concentration (ppm)	SWPAC 1984	SWPAC 1985	Decker 1985
	(% of total hours)		
0.000 - 0.009	19.2	8.1	2.0
0.010 - 0.019	9.4	12.9	5.9
0.020 - 0.029	9.6	19.0	12.8
0.030 - 0.039	9.6	17.8	18.6
0.040 - 0.049	12.9	16.4	18.6
0.050 - 0.059	12.1	12.7	13.9
0.060 - 0.069	10.1	8.0	11.4
0.070 - 0.079	8.3	3.9	6.1
0.080 - 0.089	3.2	1.3	3.4
0.090 - 0.099	0.5	0.0	1.2
>0.100	1.5	0.0	0.0

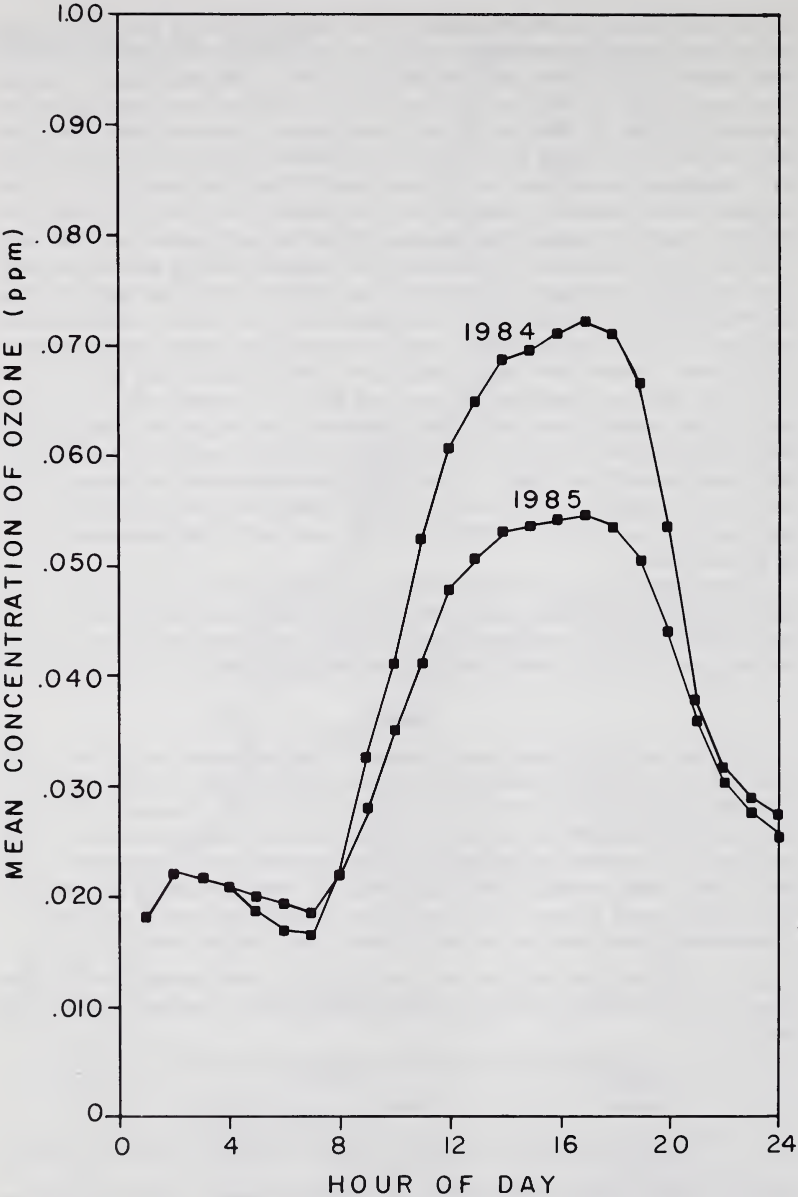

FIGURE 2. Mean hourly ozone concentrations from May 1 to August 31, 1984 & 1985 at Southwest Purdue Agriculture Center.

The diurnal patterns of hourly mean concentrations of SO_2 from May 1 to August 31 (Figure 4) indicate that SO_2 concentrations were also higher in 1984 than 1985. Sulfur dioxide concentrations were highest during the daylight hours when the O_3 concentrations were high. During each of the summers of 1984 and 1985, ambient

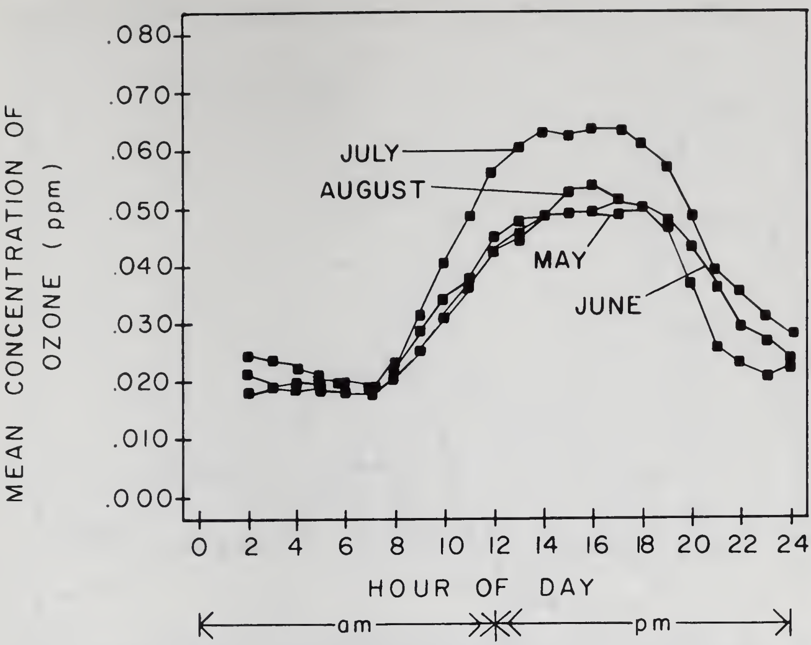

FIGURE 3. Mean hourly ozone concentrations during May, June, July, and August, 1985 at Southwest Purdue Agriculture Center.

SO_2 concentrations above 0.025 ppm occurred for a greater number of total hours in June and July than in August at SWPAC (Table 5). In 1984, the Decker site was exposed to these levels for a greater number of hours in each of June, July, and August than was the SWPAC site. Further, the hourly mean concentration of SO_2 was higher in July and August at the Decker site.

The acidity of the precipitation during the growing season at SWPAC and Decker was quite high and consistent throughout the entire season with the pH of the rain at SWPAC between 3.7 and 4.4 in all but 3 weeks throughout the growing season (Figure 5). The pH of rain at Decker was generally as acidic but was somewhat more

TABLE 5. Concentrations of sulfur dioxide (ppm) recorded at SWPAC (Vincennes) and Decker, Indiana during the summers of 1984 and 1985.

		No. Hours SO_2[1] (>0.025 ppm)		Hrly Mean of SO_2 (ppm) Levels >0.025 ppm SO_2	
Year	Month	SWPAC	Decker	SWPAC	Decker
1984	June	27	39	0.055	0.051
1984	July	29	37	0.035	0.051
1984	August	5	56	0.043	0.065
1985	June	15	—	0.038	—
1985	July	17	—	0.033	—
1985	August	11	—	0.035	—

[1]Represents numbers of hours with hourly mean SO_2 concentrations > 0.025 ppm.

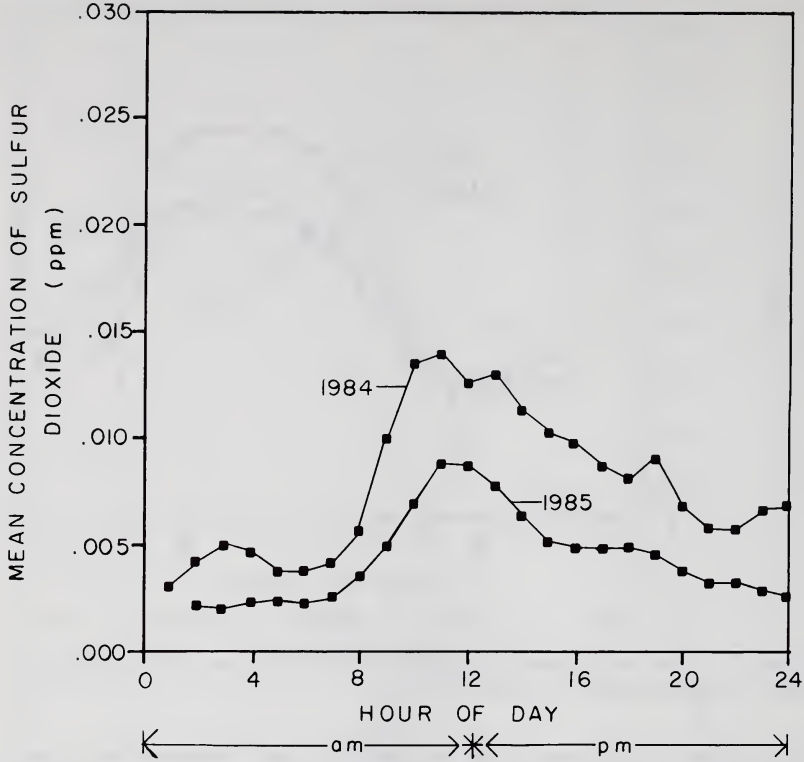

FIGURE 4. Mean hourly sulfur dioxide concentrations from May 1 to August 31, 1984 & 1985 at Southwest Purdue Agriculture Center.

variable with several of the collections exceeding a pH of 4.5 (Figure 6). The two high pH values were from contamination in the sampler. The average pH values observed at these two stations during the growing seasons indicate the acidic nature of the precipitation and is in the range similar to those summarized for the midwest in the NADP data summary for 1982 (14).

Foliar damage to bioindicators was observed at all sites located throughout the entire survey area in 1984 (Table 6) with similar results in 1985 (data not presented). The visible damage to each plant species was characteristic of ozone induced injury (8,9). Differences in the amount of injury were noted among species and sites. Tobacco (Bel W3) and beans (Pinto I-11) showed more injury than any other bioindicator; soybeans (cv. Cutler) exhibited very little foliar injury. Foliar O_3 induced injury to tobacco consisted of characteristic flecking (necrotic lesions) on the upper surface of mature leaves (Figure 7). Ozone induced injury was more severe on the tobacco cv. Bel W3 than Bel B, which is in agreement with the reported relative sensitivity of both cultivars. Foliar injury of the bean species (BBL 290, OSU 1604 and Cutler soybeans) consisted of a stippling of the upper leaf surface often preceeded by chlorosis of the interveinal leaf tissues (Figure 8). Foliar injury of squash consisted of a premature chlorosis or reddish-brown stipple of upper leaf surfaces which were "leathery" in texture. Some marginal and interveinal necrosis was observed on all bioindicators.

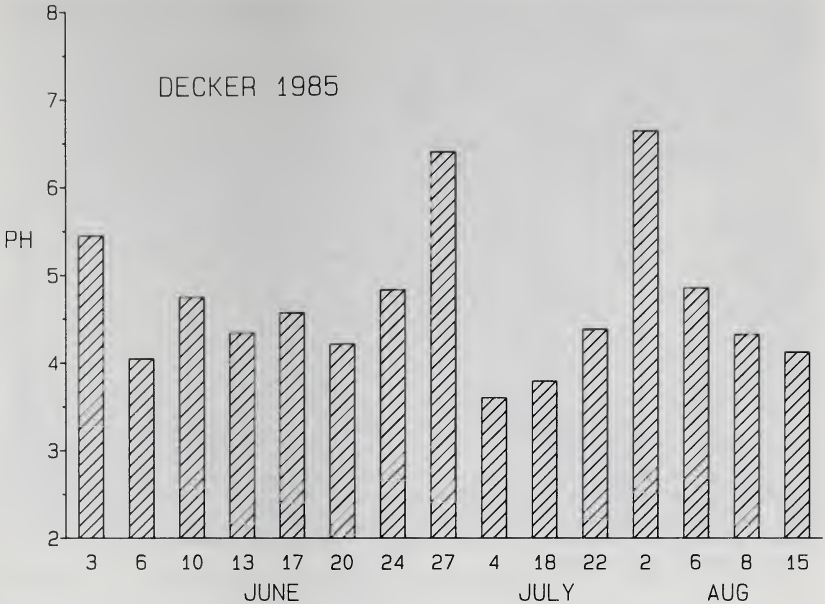

FIGURE 5. Acidity of rain during the growing season of 1985 at Decker, IN. Wet-only collections were made twice each week.

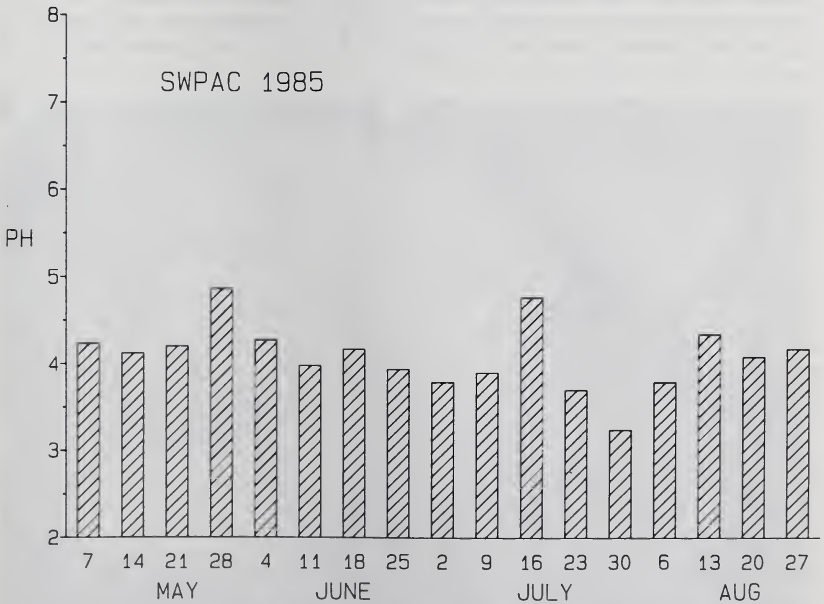

FIGURE 6. Acidity of rain during the growing season of 1985 at the Southwest Purdue Agriculture Center. Wet-only collections were made each week as a part of the NADP Network.

TABLE 6. Foliar injury ratings of bioindicators in commercial melon fields, 1984.

	Injury Ratings[1]							
	Bioindicators							Soil
Site #[2]	Bel W3 Tobacco	Bel B Tobacco	Pinto 1-11	Squash	Soybeans	OSU 1064	BBL 290	pH (water)
1				8.8	9.8	9.7	8.5	6.5
2				9.0	9.3	8.5	8.9	5.3
3				7.5	6.0	8.0	8.5	6.1
4				8.0	9.8	8.5	8.9	6.5
5	6.2	9.5	6.0	6.5	8.9	8.5	8.5	5.9
6				6.5	8.0	7.0	8.0	6.2
7				5.0	9.5	8.0	7.0	5.8
8				6.8	9.0	3.0	6.5	6.3
9				8.8	9.8	9.1	9.3	6.9
10				7.8	9.5	7.5	8.0	5.4
11	4.0	7.5	5.0	6.0	9.3	7.0	6.0	5.3
12				9.8	10.0	9.9	9.9	5.8
13				9.3	10.0	9.4	9.1	6.2
x	5.1	8.5	5.5	7.7	9.1	8.0	8.3	6.0

[1]Plants were rated during the last week of August using a rating scale of 0 to 10 with 0 = approximately all leaf area exhibiting foliage injury, 10 = absence of leaf injury.
[2]Site locations 1-3: Sullivan County; 4-11: Knox County; 12-13: Gibson County. Site 5 = SWPAC; Site 11 = Decker.

Discussion

Results from this study indicate that air pollution is present in SW Indiana in sufficient concentrations to cause injury to sensitive agricultural crops. This conclusion is supported both by the recorded readings of high concentrations of air pollutants and by the acidic nature of the precipitation at both monitoring sites. A regional air

FIGURE 7. Upper surface "flecking" on leaf of tobacco cv. Bel W-3 caused by ozone.

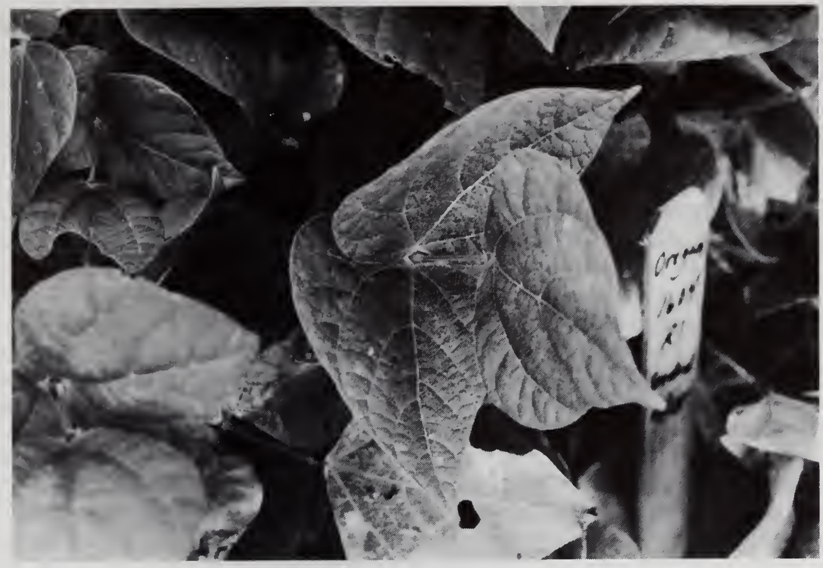

FIGURE 8. Upper surface "stippling" on leaf of bean cv. OSU 1604 caused by ozone.

quality problem is also suggested by the number of sites in which the bioindicator plants exhibited foliar injury induced by air pollution. This is in agreement with the recent study by Decoteau et al. (2) who identified ozone as the principal cause of the foliar damage to watermelons in SW Indiana.

Bioindicator plants in the southern section of the region exhibited less foliar injury than plants in the northern sites. Differences in plant injury among fields and sites may be due to differences in soil type and pH, and growing conditions between sites. However, although differences in soil pH were recorded among the sites, the visible injury was caused by air pollution and not by low pH soil or biotic stress. Tissue analysis indicated normal concentrations of manganese and magnesium in the bioindicators. Muskmelon and watermelon plants grown in the same region in low pH soils (pH <5.5) have exhibited foliar chlorosis and necrosis due to toxic levels of manganese and deficient levels of magnesium (17).

Visible injury on SO_2-sensitive squash and soybeans and an O_3-sensitive beans (BBL 290 & OSU 1605) was indicative only of O_3 damage (i.e. upper surface stippling and chlorosis) with little to no classical SO_2 injury (bifacial necrosis) observed. The high levels of ozone that persisted for several hours during the summer months caused injury to these air pollution sensitive plants. Concentrations of O_3 that can induce observable foliar injury on O_3-sensitive plants are estimated to be >0.050 ppm for 2 to 4 hour periods (13). In SW Indiana, 30-36% of the total mean hourly O_3 concentrations exceeded >0.050 ppm. In comparison, Brennan and Rhoads (1) reported significant oxidant injury on field-grown beans in New Jersey when only 3% of the total mean hourly O_3 concentrations exceeded >0.050 ppm. While most of the plant injury appears characteristic of O_3-induced injury, the role of SO_2 as an injury-inducer is not known. Ozone and SO_2 in experimental exposures with other plant species have been shown to act synergistically in causing enhanced plant injury (16). The resulting visible injury can mimic that caused by O_3 alone. While SO_2 concentrations were not high enough to cause direct foliar injury alone, the measured concentrations, which occurred during daylight hours, could enhance the ozone-injury symptoms and the interaction of O_3 and SO_2 warrants further study. Short periods of measurable SO_2 concentrations did exist during the 1984 and 1985 growing seasons with sulfur dioxide concentrations being greater during 1985. The duration of levels above background was longer at the Decker site than at SWPAC. Direct foliar injury due to acidic precipitation was not observed during the 1985 growing season. Only one collection, a pH of 3.24 at SWPAC, is in the range where foliar injury to sensitive plants has been noted in controlled studies of acid rain (7). Analysis of the precipitation for anions and cations would allow the estimation of the total acidic deposition as well as the deposition of important nutrients (S, Ca, Kg, K, and N) and should be examined.

This study has determined that air pollution is present in SW Indiana, and that ozone is in concentrations sufficiently high to result in visible injury to air pollution sensitive plant species. Further research is necessary to determine specific effects and synergistic effects of O_3, NO_x, SO_2, and the pH of precipitation and soil. The role of SO_2, O_3 and acidic deposition in predisposing agricultural crops to nutrient stress and infectious diseases warrants further investigation. Finally, continued studies are necessary to determine the effect of air pollution on the actual growth, yield, and economic impact to the agricultural and horticultural crops of Indiana.

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