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THE IMPACT OF OZONE ON AGRICULTURE AND ITS CONSEQUENCES

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ABSTRACT

Given its high level of phytotoxicity and distribution of elevated concentrations over broad geographic areas, O_3 is considered the most critical air pollutant affecting vegetation in the United States. Diverse experimental methods have been used to assess the impacts of O_3 on the crop yield. Comparisons of plant growth and yield in charcoal-filtered or unfiltered air and the use of chemical protectants show that ambient O_3 levels will reduce the growth and yield of numerous plant species. Ozone studies in open-top field-exposure chambers have provided exposure-response functions needed to evaluate the economic impacts of O_3 on agriculture. Exposure-response functions have been developed for a range of legume, grain, fiber and horticultural crops. Yield reductions (10%) were predicted for several crop species when the 7-hr seasonal mean concentration exceeded 0.04 to 0.05 ppm. For some sensitive cultivars of wheat, kidney bean and soybean, 10% yield reductions occurred at 7-hr mean concentrations of 0.028 to 0.033 ppm. Recent studies, using exposure-response functions developed in open-top chambers, have attempted to assess the national economic consequences of O_3 effects on agriculture. These studies indicate that elevated O_3 concentrations are costing U.S. agricultural producers and consumers between 1.2 and 2.4 billion dollars annually.

INTRODUCTION

Ozone exerts a phytotoxic effect on vegetation only if enough diffuses from the ambient air into the leaf's sensitive cellular sites to cause an impact. Foliar injury is one of the earliest and most obvious manifestations of an O_3 effect, but impacts can also occur on other plant organs, causing effects ranging from reduced plant growth and decreased yield to changes in crop quality and alterations in susceptibility to abiotic and biotic stresses.

Yield Loss -- Definition

Yield loss is defined as an impairment or decrease in the intended use of the plant or its product. This concept of yield loss includes reductions in aesthetic values, the occurrence of foliar injury (changes in plant appearance), and losses in weight, number, or size of the plant organ that is normally harvested. Yield loss may also include changes in crop quality.

Yield Loss -- Methods

To assess the impact of O_3 on plant yield, diverse experimental methods have been used, ranging from studies under highly controlled conditions to exposures using field-exposure systems and chamberless systems, including chemical protectants. To determine the impact of O_3 on plant growth and yield and to provide data for economic assessments, the experimental conditions must minimize deviations from the typical environment in which the crop(s) is grown. It is also important to insure that the experiment exposure regimes are representative of the pollutant concentration range and frequency for the area in which the crop is grown or for which inferences are to be made.

Open-top field exposure chambers (ref. 1, 2) are used most frequently to estimate yield losses because they permit creation of a range of O_3 exposures and can approximate typical cultural conditions. The open-top design permits plants to be grown in soil under environmental conditions comparable to the ambient. The design permits the determination of the effects of the ambient pollutant burden on plant yield by comparing the differences in plant yield between filtered and unfiltered chambers. Plants can be exposed to charcoal-filtered air and a range of O_3 concentrations above and below the current ambient level so that exposure-response functions can be developed (ref. 3, 4).

Chemical protectants have been used to avoid possible chamber influences on yield loss estimates (ref. 5). The crops are grown under typical field conditions, treated with protectant and exposed to ambient pollution. Yield loss is obtained by comparing plant yield from plots treated with the O_3 protectant to the yield from untreated plots. However, using the protectant, only a single pollutant treatment is possible at a given location; consequently exposure-response functions cannot be developed. Also, the data must be interpreted carefully because the chemical protectant may alter plant performance.

ESTIMATES OF YIELD LOSS

Ambient Air

Early research comparing crop yields between charcoal-filtered and unfiltered air documented that the ambient level of photochemical oxidants reduced yield of citrus, grape, tobacco, cotton, and potato (ref. 6). Subsequent studies confirmed that ambient levels of O_3 were high enough to impair plant yield. For example, ambient O_3 reduced the yields of tomato -- 33% (ref. 7), bean -- +1 to 26% (ref. 7-9), soybeans -- 20% (ref. 10, 11) and two sweet corn cultivars -- 9 and 28% (ref. 12).

Chemical Protectants

Chemical protectants have been used to estimate the impact of ambient O_3 on the yield of several crop species (Table 1). Using this approach, yields were reduced 18 to 41% when the ambient oxidant concentration exceeded 0.08 ppm for 5 to 18 days over the crop's growing season. These data support the conclusions from studies comparing yield in charcoal-filtered and unfiltered air, i.e., ambient levels of O_3 can be high enough to impair crop production.

TABLE 1

The effects of ambient O_3 on crop yield as determined by the use of chemical protectants.[a]

Species	Yield reduction % of control	O_3 exposure	Reference
Beans (green)	41	> 0.08 for total of 27 hr over 3.5 months	13
Onion	38	> 0.08 on 5 days out of 48	14
Tomato	30	> 0.08 on 15 days over 3 months	15
Bean (dry)	24	> 0.08 on 11 days (total of 34 hr) over 3 months	16
Tobacco	18	> 0.08 on 14 days during the summer	17
Potato	36	> 0.08 ppm on 18 days (total of 68 hr) over 3 months	18
Potato	25	---[b]	19

[a] All the species were treated with the antioxidant EDU except the bean study (ref. 13) which used the systemic fungicide benomyl. Yield reduction was determined by comparing the yields of plants treated with chemical protectants (control) to those that were not treated.

[b] This study was run over 2 years when the O_3 doses were 65 and 110 ppm/hr, respectively, but the yield loss was similar both years.

Controlled Exposures

Most experimental techniques that assess yield loss from controlled exposures have used a range of O_3 concentrations and regression approaches to develop exposure-response functions which relate crop yield loss to O_3 exposure. The regression approaches permit the estimation of the O_3 impact on plant yield over the range of concentrations and it is possible to interpolate between treatment means; this is not possible with analysis of variance methods. Most of the currently available yield loss functions (ref. 3, 20) have expressed the O_3 exposure as the 7-hr (9:00 AM until 3:59 PM) seasonal mean concentration.

Examples of exposure-response functions are shown in Figure 1. A Weibull function (ref. 21) was used to model the change in crop yield in relation to the O_3 concentration. The derived exposure-response functions can be used to determine the concentrations predicted to cause a specific yield loss or to estimate the predicted yield loss that would result from a specific O_3 concentration. Both approaches have been used to summarize the data on crop responses to O_3 using a Weibull function. As an example, the O_3 concentrations

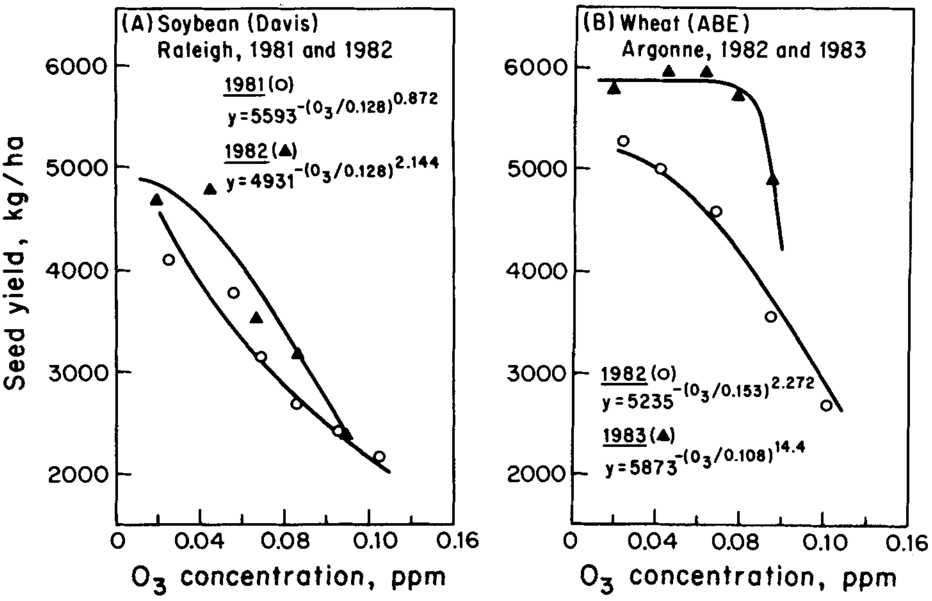

Figure 1. Examples of the effects of O_3 on the yield of soybean and wheat cultivars over two years. The O_3 concentrations are expressed as 7-hr seasonal mean concentrations. The cultivars were selected to illustrate year-to-year variation in plant response to O_3. The soybean data are from Heck et al. (ref. 20) and the wheat data are from Kress et al. (ref. 22).

predicted to cause a 10 or 30% yield loss have been estimated (Table 2). For approximately 56% of the species/cultivars listed, mean yield reductions were predicted to exceed 10% when the 7-hr seasonal mean O_3 concentration exceeded 0.05 ppm. In sensitive crops, 7-hr seasonal mean concentrations of 0.028 to 0.033 ppm were predicted to cause a 10% yield loss in Vona wheat, kidney bean, and Hodgson soybean. At a 7-hr seasonal mean O_3 concentration of 0.04 ppm, mean yield reductions ranged from 0 in sorghum, barley, and a corn cultivar to a high of 28.8% in Vona wheat.

The grain crops were generally less sensitive to O_3 than were the other species (Table 2). For all grain crops, mean yield reductions at 7-hr seasonal mean concentrations of 0.04 ppm were predicted to be less than 5% except for the Roland and Vona wheat cultivars. The data also demonstrate that sensitivity differences within a species may be as large as differences between species. For example, at 0.04 ppm O_3, estimated yield losses ranged from 2 to 15% in soybean and from 0 to 28% in wheat.

TABLE 2

Compilation of O_3 concentrations predicted to cause 10% and 30% yield losses as well as yield losses predicted to occur at 7-hr seasonal mean O_3 concentrations of 0.04 and 0.06 ppm.[a]

Species	7-hr seasonal mean O_3 concentrations, ppm predicted to cause yield losses of:		Percent yield losses predicted to occur at 7-hr seasonal mean O_3 concentration of:	
	10%	30%	0.04 ppm	0.06 ppm
Legume Crops				
Soybean, Corsoy	0.048	0.082	6.4	16.6
Soybean, Davis (81)	0.038	0.071	11.5	24.1
Soybean, Davis (CA-82)	0.048	0.081	6.4	16.5
Soybean, Davis (PA-82)	0.059	0.081	2.0	10.4
Soybean, Essex	0.048	0.099	7.2	14.3
Soybean, Forrest	0.076	0.118	1.7	5.3
Soybean, Williams	0.039	0.093	10.4	18.1
Soybean, Hodgson	0.032	0.066	15.4	18.4
Bean, Kidney	0.033	0.063	14.9	28.0
Peanut, NC-6	0.046	0.073	6.4	19.4
Grain Crops				
Wheat, Abe	0.059	0.095	3.3	10.4
Wheat, Arthur 71	0.056	0.094	4.1	11.7
Wheat, Roland	0.039	0.067	10.3	24.5
Wheat, Vona	0.028	0.041	28.8	51.2
Wheat, Blueboy II	0.088	0.127	0.5	2.0
Wheat, Coker 47-27	0.064	0.107	2.2	8.4
Wheat, Holly	0.099	0.127	0.0	0.9
Wheat, Oasis	0.093	0.135	0.4	2.4
Corn, PAG 397	0.095	0.126	0.3	1.5
Corn, Pioneer 3780	0.075	0.111	1.4	5.1
Corn, Coker 16	0.133	0.175	0.0	0.3
Sorghum, DeKalb-28	0.108	0.186	0.0	2.7
Barley, Poco	0.121	0.161	0.0	0.5
Fiber Crops				
Cotton, Acala SJ-2 (81)	0.044	0.096	8.3	16.2
Cotton, Acala SJ-2 (82)	0.032	0.055	16.1	35.1
Cotton, Stoneville	0.047	0.075	4.6	16.2
Horticultural Crops				
Tomato, Murrieta (81)	0.079	0.108	0.8	3.7
Tomato, Murrieta (82)	0.040	0.059	10.3	31.2
Lettuce, Empire	0.053	0.075	0.0	16.8
Spinach, America	0.046	0.082	6.8	17.2
Spinach, Hybrid	0.043	0.082	2.6	9.2
Spinach, Viroflay	0.048	0.080	6.0	16.7
Spinach, Whiter Bloom	0.049	0.080	5.8	16.5
Turnip, Just Right	0.043	0.064	7.7	24.9
Turnip, Pur Top W.G.	0.040	0.064	10.1	26.5
Turnip, Shogoin	0.036	0.060	13.0	29.7
Turnip, Tokyo Cross	0.053	0.072	3.3	15.6

[a] The yield losses are derived from Weibull equations and are based on the control yields in charcoal-filtered air. Data are derived from exposure-response functions (ref. 20).

Ambient Air Quality -- Relationship to Yield Loss

An understanding of ambient concentrations of O_3 is needed to place the concentrations predicted to cause 10 and 30% yield losses in perspective. For example, air monitoring data for a single O_3 season were obtained from rural or remote monitoring sites throughout the United States (Table 3). For these sites, the 7-hr seasonal mean O_3 concentration averaged 0.044 ppm with a range of 0.019 to 0.057 ppm. This range encompasses the same concentration range predicted to cause a 10% yield loss in numerous crop species/cultivars (Table 2). The 12-hr seasonal mean at most sites is approximately equal to the 7-hr seasonal mean. At most monitoring sites, the number of hours greater than 0.08 ppm was similar to or greater than the exceedances associated with crop yield loss (Table 1).

TABLE 3

Examples of ambient ozone concentrations at rural and remote monitoring sites.[a]

Air Quality Statistic	Mean	St. Dev.	Max.	Min.
7-hr Seasonal Mean	0.043	0.007	0.057	0.019
12-hr Seasonal Mean	0.041	0.006	0.055	0.021
Hours Above 0.08 ppm	106	104	474	0
Hours Above 0.10 ppm	19	34	195	0
Hours Above 0.12 ppm	4	12	74	0

[a] Data courtesy of Ted Johnson, PEI Associates, Durham, North Carolina. Mean concentrations are expressed in ppm. The data are from 82 rural and remote monitoring sites from 32 states across the U.S. for a single year (ozone season) between 1982 and 1984.

Yield Loss -- Physiological Basis

Specific studies have not clearly established the cause(s) of the yield losses but several factors singly or in combination probably contribute. Ozone can reduce flowering, seed set, and fertilization processes in plants (ref. 23-27). Experiments have suggested that part of the O_3 impact on yield results from a simulation of leaf drop and senescence (ref. 28-31). Photosynthesis, as measured by gas-exchange, is inhibited by O_3 (0.05 ppm and higher) (ref. 6, 32-34). Biochemical studies have also shown that O_3 (0.12 ppm for 2 hr) inhibits an enzyme which catalyzes the assimilation of CO_2 (ref. 35). Ozone also alters the pattern by which photoassimilate is partitioned through the plant with less of it being translocated to the roots and reproductive organs (ref. 36-40).

Yield Loss -- Factors Affecting

Numerous factors, ranging from abiotic and biotic factors to the presence of other pollutants and the temporal dynamics of the exposure, can modify plant response to O_3. However, factors influencing plant water relations (relative humidity and soil moisture stress) and the presence of other pollutants are thought to be the most important.

Plant response to O_3 tends to increase with increasing relative humidity (ref. 6). The relative humidity effect appears to be related to stomatal aperture, which tends to increase with increasing relative humidity. McLaughlin and Taylor (ref. 41) demonstrated that plants absorb significantly more O_3 at high humidity than at low humidity.

As soil moisture decreases, plant water stress increases and there is a reduction in plant sensitivity to O_3 (e.g., ref. 6, 42). The reduced O_3 sensitivity is apparently related to stomatal closure, which reduces O_3 uptake (ref. 6, 43, 44). Water stress does not confer a permanent tolerance to O_3; once the water stress has been alleviated, the plants regain their sensitivity to O_3 (ref. 44).

Menser and Heggestad (ref. 45) provided the initial impetus to study the interaction of O_3 with SO_2. They showed that Bel W-3 tobacco plants exposed to O_3 (0.03 ppm) or SO_2 (0.24 to 0.28 ppm) were uninjured but that substantial foliar injury resulted when the plants were exposed to both gases simultaneously. Subsequent studies have confirmed and extended the observation that combinations of O_3 and SO_2 may cause more visible injury on many species than expected, based on the injury caused by the individual gases (e.g., ref. 43, 46, 47). This injury enhancement is most common at low concentrations of each gas and also when the amount of foliar injury induced by each gas, individually, is small. At higher concentrations or when extensive injury occurs, the effects of the individual gases tend to be less than additive.

Field studies have been conducted to determine the influence of SO_2 on plant response to O_3 on several plant species: soybean (ref. 48, 49), beans (ref. 9, 50), and potatoes (ref. 51). In these studies, O_3 reduced plant yield but SO_2 had no significant effect and did not interact with O_3 to reduce yield unless the SO_2 exposure concentrations and frequency of occurrence were much greater than those typically found in the ambient air in the United States.

Many of the studies to determine the influence of pollutant combinations on plant growth and yield have used experimental exposures more intense than those found in the ambient air; consequently the applicability of the yield results from most pollutant combination studies to ambient conditions is not known. An analysis of ambient air monitoring data indicated that the joint co-occurrence of pollutants tended to be infrequent (ref. 52).

ECONOMIC CONSEQUENCES OF OZONE EXPOSURE

Various methods have been used for estimating economic losses, from simple monetary calculations to more complex economic assessment methodologies. The simple procedures calculated monetary effects by multiplying predicted yield or production changes resulting from exposure to O_3 by an assumed constant crop price. This procedure fails to account for possible price changes resulting from yield changes and does not account for the processes underlying economic response.

To conduct a reliable economic assessment, several types of information are needed -- data to relate crop response to O_3 concentrations under actual field conditions and air quality data to describe current or hypothetical O_3 exposures to crops in each production area. The assessment methodology should represent the economic behavior of producers and consumers as they adjust to changes in crop yields and prices that may accompany changes in O_3 air quality.

National-level estimates of the economic impact of O_3 on agriculture (including both producer and consumers) range from 1.2 to 2.4 billion dollars annually (Table 4). The current dollar estimates of crop loss are useful primarily as indicators of the magnitudes of impact. A full accounting of the economic mechanisms underlying agricultural production is required to provide definitive estimates of agricultural losses. Such an assessment should include both annual and perennial crops and the associated dynamics of agricultural production. The assessment should also include factors that affect plant response to O_3 such as the temporal nature of the exposure and the influence of plant water stress on exposure-response functions.

SUMMARY

Several lines of evidence lead to the conclusion that O_3 is the most important air pollutant affecting vegetation in the United States. Air monitoring studies have found elevated O_3 levels in many areas and vegetation studies have confirmed that these levels are high enough to impact crop yield. Controlled field exposures to O_3 have substantiated the impact of O_3 on crop yield and permitted the development of exposure response functions for economic assessments. Detailed economic analyses have found that O_3 causes significant impacts on both producers and consumers.

TABLE 4

Estimates of national economic consequences of ozone exposure.

Crops	Annual benefits of control, $ million	Additional Comments	Reference
3 crops: corn, soybeans, and cotton. Two corn cultivars, three soybean, two cotton.	$2.2 in 1980 dollars.	Economic estimate measured in terms of changes in consumer and producer surpluses associated with the change in O_3.	53
4 crops: corn, soybeans, wheat, and cotton. Two cultivars for corn and cotton, three for soybeans and wheat.	$2.4 in 1980 dollars.	Same as Adams and Crocker (ref. 53). Linear functions result in higher yield losses and hence higher economic loss estimates. Reported estimate ($2.4 billion) is for quadratic response function.	54
5 crops: corn, soybeans, wheat, cotton, and peanuts. Multiple cultivars of each crop except peanuts.	$1.2 in 1978 dollars.	In addition to measuring the change in economic surplus for various assumed O_3 levels, the analysis also includes an examination of the sensitivity of the estimates of the nature of the demand relationships used in the model.	55
6 crops: barley, corn, soybeans, cotton, wheat, and sorghum. Multiple cultivars used for each crop except barley and grain sorghum; two for cotton, three for wheat, two for corn, and nine for soybeans.	$1.7 in 1980 dollars.	Consumer surplus estimated for both domestic and foreign markets; producer surplus nationally by region. The analysis includes a range of economic estimates reflecting changes in response and O_3 data and assumptions.	56

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