Air Pollution and Farm-Level Crop Yields: An Empirical Analysis of Corn and Soybeans

David A. Westenbarger and George B. Frisvold

While many studies have estimated the impacts of air pollution on crop yields on experimental plots, few have estimated these impacts under actual farm production conditions. This study econometrically estimates the impact of air pollution on corn and soybean yields, controlling for weather, soil quality and management practices, using farm-level data for the eastern United States. Ozone pollution was found to reduce yields for both crops. The mean elasticity of yield with respect to ozone exposure was −0.19 for corn and −0.54 for soybeans. The benefits of ozone standards to protect crops, measured in terms of crop revenues, range from $17 to $82 million depending on the stringency of the standard. Over 85 percent of the revenue gains are captured by three states: Maryland, North Carolina, and Virginia.

The effects of air pollution on vegetation have been examined as far back as the 19th century when scientists studied unexplained leaf damage to plants growing near factories. Since then, scientists have refined their processes for identifying the causes of leaf damage, reduced growth and other injury from airborne pollutants (Heck, 1989 provides an extensive survey). Using controlled field chamber experiments, plant scientists have estimated the impacts of air pollutants on crop yields and then used the estimated parameters to extrapolate to region-level damages. Much of this work has been carried out as part of U.S. Environmental Protection Agency's (EPA) National Crop Loss Assessment Network (NCLAN) (Heck, 1989).

These studies have been instrumental in obtaining knowledge about plant responses to pollution exposure and have been widely used as the basis for economic assessments of pollution damages. There are, however, certain limitations with extrapolating from field trial experiments to economic models. First, the NCLAN studies reported relationships between yield and seasonal mean concentrations of ozone. Seasonal mean concentrations, however, do not capture important components of ozone exposure that affect plant development such as peaks in exposures. There is significant evidence that an appropriate exposure index should weight higher concentrations more heavily than lower ones (Lefohn, 1992). The National Acid Precipitation Assessment Program (NAPAP) concluded that long-term seasonal mean concentrations may not be an appropriate measure of exposure (Lefohn, 1990). Second, experimental exposure regimes generally do not correspond well to ambient exposure regimes. Musselman *et al.* found that adjusting experimental exposures to more closely mimic ambient exposures resulted in higher estimates of yield loss. Third, controlled-chamber experiments on experimental plots may not accurately reflect actual pollution effects on farm-level production. Many experimental studies abstract from farm-level weather and soil conditions as well as economic adjustments in input use and management practices.

This study econometrically estimates the impact of air pollution on corn and soybean yields, controlling for weather, soil characteristics and management practices, using farm-level data for the eastern United States. While many studies have estimated the impacts of air pollution on crop yields on experimental plots, few have estimated these impacts under actual farm production conditions (Garcia *et al.*; Leung *et al.*). The study also employs a cumulative exposure index which has been found to be a better predictor of the impacts of ozone on vegetation than seasonal mean measures (Lefohn et al., 1992; Lefohn et al., 1988;

The authors are economists with the Natural Resources and Environment Division of the Economic Research Service, U.S. Department of Agriculture, Washington, DC. The views expressed are those of the authors and do not necessarily represent the views of USDA.

The authors gratefully acknowledge the helpful comments of the editor and three anonymous journal reviewers.

Lee et al., 1988). Ozone pollution was found to reduce yields for both crops. The mean elasticity of yield with respect to ozone exposure was -0.19 for corn and -0.54 for soybeans. The final portion of the paper estimates benefits of alternative ozone standards to protect vegetation. Currently, the primary (health effects) and secondary (economic effects) national ambient air quality standards (NAAQS) are both set at an hourly average concentration of 0.12 ppm, not to be exceeded more than one day in any 12-month period. The secondary standard is intended to protect against crop and forest damage, as well as visibility impairment and deterioration of structures. Primary and secondary standards are not required to be identical and there is substantial evidence that the current 0.12 ppm standard is *not* appropriate for protecting vegetation. The main result of this exercise is that although the overall regional impacts of the standards considered were modest, there were significant productivity benefits to high ozone exposure counties.

Background

There is significant evidence that tropospheric ozone can have serious negative effects on crop yields by inhibiting photosynthesis and nutrient uptake (Barse et al., 1985; Heck 1987; Heck et al., 1984; Heggestad and Lesser, 1990). Ozone has been linked to leaf damage and reduced seed size which correlate directly to reduced yields (Barse et al. 1985; Heck et al., 1985). Field studies conducted on individual crops (Oshima et al., 1976; Leung et al., 1982; Foster et al., 1983; Heck et al., 1984; Miller et al., 1989; Heggestad and Lesser, 1990) have found yield reductions of anywhere from negligible amounts to over 50 percent, depending on the cultivar and ozone exposure regimen.

Ozone (O_3), a photochemical oxidant, interferes with plant respiration and photosynthesis (Heck 1984). It is created from the mixture of hydrocarbons (e.g. butane and toluene) and nitrogen oxide compounds (NO_x) emitted from automobiles (and other sources). The Office of Technology Assessment (1984) has reported that "up to 90 percent of the damage to crops from air pollutants may be due to ozone . . .," and that "ozone causes about a 6- to 7-percent loss of U.S. agricultural productivity." Leduc and Sakamoto (1988) conclude that "70 percent of damage to vegetation by air pollutants in the U.S. results from O_3 concentrations," and Adams et al. (1986) estimate that a 25 percent increase in tropospheric ozone concentrations would result in a $2.4 billion welfare loss. Additionally, Heck et al. (1982) estimated that reducing ozone concentrations to 0.025 part per million (ppm) would result in a $3.1 billion increase in yields of four major crops: wheat, soybeans, corn and peanuts.

Two methods have been employed to estimate the effects of air pollution on vegetation. In the first, the biological method, a pollutant is introduced into a controlled environment (e.g. in closed field chambers on experimental plots) in precise amounts and the response of the plants is monitored over the growing season. The results are used to fit dose-response functions that correlate the dosage of pollutant with plant yield or biomass production. Extrapolations are then made based on the experimental dose-response functions to calculate the losses that would result from various levels of pollution. The National Crop Loss Assessment Network (NCLAN), among others, utilized this approach to study a wide range of crops and cultivars. These studies have been instrumental in determining the precise response mechanisms of various plants.

There are limitations to this approach, however. First, these experiments are designed to maximize yields given certain production conditions. While this is appropriate from a scientific perspective, an economic approach does not impose such yield-maximizing behavior. As Leung et al. (1982) note, "[d]amage functions that are derived from laboratory or controlled experiments are not necessarily correlated closely with actual farm situations." Experimental plot studies employ other inputs to maximize yields for given levels of pollution. There is no *a priori* reason to expect profit or utility maximizing farmers to follow such a strategy (Garcia et al., 1986). Neither are farmers likely to encounter similar irrigation, fertilization, or other factors in levels resembling those in experimental environments. Further, this situation imposes fixed technological constraints on the producer, including the mix of inputs and specific production practices (e.g. method of tillage, pesticide use), over which the producer would be expected to exercise a great deal of discretion. In short, extrapolating damage estimates from field experiments to region-level damages ignores certain scale-, technology- and market-specific problems that an economic approach is designed to incorporate.

A third problem encountered in most of the studies of this type is reliance on an unsuitable measure of ozone exposure, namely a 7- or 12-hour mean index. While these indexes were chosen to account for daylight exposures that are considered to be most important in determining plant response, an index that averages exposures over a period ignores the two components of exposure that have been determined to be critical for assessing phytotoxic effects, namely peak exposures and chronic low dosages above a threshold (Lefohn et al., 1988).

The other method, the observational approach, uses econometric estimation to draw conclusions based on empirical observations of air pollution and agricultural productivity. This approach allows for changes in economic behavior by producers due to changes in environmental factors. The main stumbling block to performing this type of research has been the incompatibility between air pollution data and indicators of agricultural productivity. Recent work by Westenbarger and Frisvold (1994) has overcome this obstacle by mapping pollution data collected at monitoring stations to a two-dimensional surface and linking values from this surface to agricultural production data collected in the field. Using this data, we incorporate information on actual farm production practices into an economic model that allows estimation of the impacts of air pollution on corn and soybean yields.

The Model

Yield functions were estimated from a cross section of 536 farm fields for corn and 469 fields for soybeans in the eastern United States for the year 1990.[1] Corn and soybeans are the two most important crops grown in the region, and together account for over one third of the value of all crops grown in the U.S. ($18.1 billion for corn, $11.0 billion for soybeans). In 1990, the eastern region produced 15.8 percent of the total U.S. corn crop and 11.7 percent of the U.S. soybean crop. This region was chosen for two reasons. First, portions of this region experience some of the highest levels of air pollution in the nation so that potential problems may be more acute there. Second, a large number of air pollution monitoring stations are concentrated in this area so that a more reliable estimation of air pollution indexes is possible.

Previous econometric studies have found ozone to have a statistically significant impact on particular crops at the farm (Garcia et al., 1986) and regional (Leung et al., 1982) levels. Garcia et al. used a modified translog profit function to estimate the economic damage to cash grain farmers in Illinois due to ozone exposure. The model included variables for ozone as well as precipitation and temperature. The following linear production functions were fit to cross-section data for each crop for 1990:

$$\begin{aligned} y_i = {} & \beta_0 + \beta_o\, Ozone_i + \beta_N\, Nitrogen_i \\ & + \beta_S\, RKLS_i + \beta_I\, Irrigation_i \\ & + \beta_B\, Rotation_i + \beta_P\, Plant_i \\ & + \beta_R\, Rain_i + \beta_{RR}\, Rain^2{}_i \\ & + \beta_C\, Cool_i + \beta_H\, Hot_i \\ & + \epsilon_i \qquad (1) \end{aligned}$$

Linear models were found to perform better than logarithmic or translog specifications. As Hansen (1991) explains "Commonly estimated yield functions are linear across most inputs with quadratic or logarithmic measures of particular inputs with nonconstant marginal physical products." Mulchi also found that linear exposure-yield relationships held for ambient (as opposed to experimental) levels of ozone exposure.[2]

The Data

Cross-sectional data on yields and management practices come from the USDA 1990 Cropping Practices Survey. Weather, soil quality and air quality data were obtained from other sources (discussed below) and matched to field-level observations. Table 1 shows definitions and descriptive statistics for variables used in the regression equations. The dependent variable in both models, y_i, is corn or soybean yields measured in bushels per acre. *Nitrogen* is pounds of active ingredient of nitrogen fertilizer per acre applied to the field. Potassium and phosphate were excluded because of extreme multicollinearity among the three fertilizers.

Rotation is a binary variable denoting corn / soybean rotations. In the corn regression equation, the variable equals one if soybeans were planted the previous year on the field and zero otherwise. In the soybean equation, the variable equals one if corn was planted the previous year on the field and zero otherwise. Soybeans are often grown in rotation with corn, a heavy nutrient feeder, to provide additional nitrogen to the soil and hence improve the productivity of the corn crop. While it is widely known that corn benefits from the nitrogen fixing properties of legumes like soybeans when grown in rotation, studies have found that soybean yields are enhanced when grown in rotation with corn, even more so than when soybeans are grown

---

[1] These include Delaware, Maryland, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Virginia, West Virginia, and the New England States.

Table 1. Yield Function Definitions and Descriptive Statistics

Variable	Description	Corn		Soybeans	
		Mean	St. Dev.	Mean	St. Dev.
Yield	bu/acre of output	110.21	34.04	33.96	11.51
Nitrogen	lbs/acre of active ingredient	119.69	77.19	8.95	15.31
RKLS	Index of soil erodibility	6.89	6.80	5.39	5.32
Rotation	Dummy Variable: = 1 if corn (soybeans) grown previously on soybean (corn) plots = 0 otherwise	0.45	0.50	0.38	0.49
Irrigation	Dummy Variable: = if 1 field irrigated = 0 otherwise	0.04	0.20	0.01	0.11
Plant	Julian planting date	124.37	18.41	108.35	68.99
Rain	Spring precipitation (in.)	12.81	1.96	12.37	1.88
Cool	Dummy Variable: = 1 if summer temperature below 72 degrees F = 0 otherwise	0.15	0.35	0.09	0.28
Hot	Dummy Variable: = 1 if summer temperature above 79 degrees F = 0 otherwise	0.20	0.40	0.25	0.44
Ozone	Summer cumulative exposure index for ozone (ppm-h)	18.03	3.28	19.07	3.23

continuously (Meese et al., 1991; Lund, et al., 1993).

Irrigation is a binary variable that equals one if the field was irrigated, while *Plant* is the planting date expressed as the Julian date the crop was planted (the number of days since January 1st). *RKLS* is a measure of soil erodibility taken from the Universal Soil Loss Equation (USLE) that is a composite index of various soil characteristics, including soil loss tolerance factor, erodibility and texture of the soil, rainfall, and cropping practices and erosion control methods used. The *RKLS* variable comes from the National Resources Inventory (USDA, SCS) and measures differences in soil characteristics across the region.

Data on precipitation and temperature were obtained from the National Oceanic and Atmospheric Administration (NOAA) and published in Teigen and Singer (1992). *Rain* and $Rain^2$ are the total spring (April–June) precipitation in the county, in inches, and the total precipitation squared. Including a quadratic term implies an optimal level of rainfall (Hansen 1991). Similar temperature variables were tested but these variables were excluded because they exhibited strong positive correlations with the ozone variable. This result seems reasonable considering that higher temperatures would correspond with more sunlight and thus elevated levels of ozone formation. To counter this problem, two binary variables, *Hot* and *Cool,* were included which were less highly correlated with the pollutant variables. *Hot* equals one if the average summer temperature at the sample point was above 79 degrees Fahrenheit, while *Cool* equals one if the temperature was below 72 degrees. These points were chosen to include points with temperatures greater than one standard deviation above or below the sample means.

Construction of Ozone Variable

Ozone is a cumulative index of ambient summer (July–September) ozone concentrations developed by Westenbarger and Frisvold (1994) from hourly observations, measured in parts per million, weighting the observations using a sigmoidal pattern (see Lefohn and Runeckles, 1987). The weighting technique provides a statistic that captures important components of ozone exposure that affect plant development, including peaks, chronic exposures, and duration, better than an average or peak indicator alone.

Ozone data were obtained from EPA's Aerometric Information Retrieval System (AIRS), Research Triangle Park, North Carolina. Data from monitoring stations were converted to a two-dimensional grid, which was then used to assign pollution values to the points in the survey, using the kriging procedure. A number of studies of atmospheric pollution have used the kriging method to convert point-source data to geographic areas (Lefohn et al., 1987; Bilonick, 1988; Adams et al., 1986; Kopp et al., 1984). Kriging, used for performing analyses of spatially distributed data, is a weighted moving average method that interpolates values from point sample data to an *n*-dimensional grid, weighting the estimates by distance and direction between samples. The procedure "can be defined as a best linear unbiased estimator of a spatial variable at a particular site or geographic area. Kriging assigns low weights to distant samples and vice versa, but also takes into account the relative position of the samples to each other and the site or area being estimated" (Lefohn et al. 1990). (Isaaks and Srivastava (1989) provide extensive discussion of the kriging method). County-level indexes of ozone concentrations were constructed using averages of block estimates, weighted by the proportion of each block overlapping a county. Kriged estimates were used by Garcia et al. (1986), for example, in their analysis of cash grain farmers in Illinois.

Because ozone is a gas and is very volatile, it is difficult to quantify an 'exposure.' Scientists have tried to determine the various parameters of ozone exposure that are most important to plants including level of exposure, hour of the day, duration and respite period between exposures. Ozone monitoring stations measure the level of ozone in the atmosphere on a continuous basis and report hourly averages. Researchers have experimented with numerous ozone index designs including seasonal seven- and twelve-hour averages of ozone readings during daylight hours, averages and sums of all ozone readings over a given threshold value (e.g. 0.08 ppm) for a season, sums of maximum values for each day during a period, counts of all ozone readings over a certain threshold value, along with other variations.

Several problems arise with these indicators, however. For instance, an infinite number of possible temporal distributions could produce the same seasonal average and these regimes would not have the same effect on plant growth. Also, a sum of values over a threshold relies on proper selection of the threshold, while also ignoring lower values which, though maybe not as important as the higher values, may in fact affect plant growth. In 1988, EPA concluded that "long-term averages, such as the 7-hour seasonal mean, may not be adequate indicators for relating ozone exposure and plant response," (Lefohn et al., 1990).

To address some of these problems, Lefohn and Runeckles (1987) proposed a cumulative exposure index (CEI) that weights each hourly reading according to a sigmoidal weighting scheme. This method multiplies each hourly reading by a weight between zero and one based on the value of the reading. They tested various configurations and chose the W126 model as the best for addressing plant exposure questions. The CEI is the weighted sum of hourly ozone exposures, measured in weighted parts per million / hour (ppm-h) and is of the form:

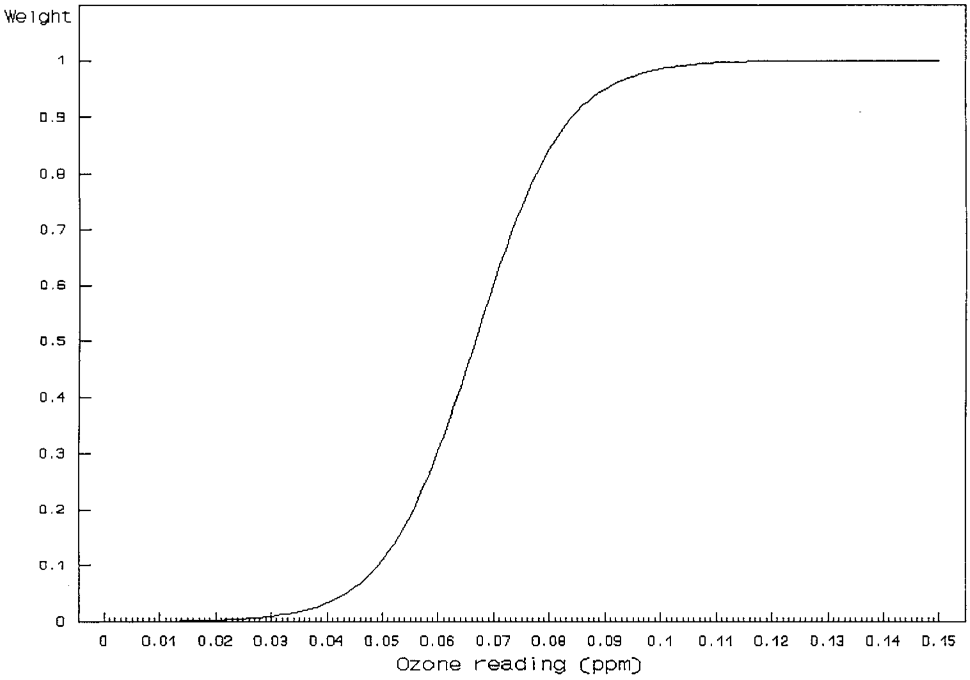

Figure 1. Sigmoid Weighting Function

$$w_i = \frac{1}{1 + Me^{-Ac_i}}$$

where w_i is the weighting factor, c_i is the ozone concentration (measured in ppm), while $A = 126$ (for the W126 index) and $M = 4403$ are constants (Lefohn and Runeckles, 1987). Each hourly concentration reading (c_i) is multiplied by its corresponding w_i and summed for the period. These aggregates are then kriged over the region to create county-level exposure indexes.

Figure 1 displays the sigmoid weighting function. The parameters M and A were chosen to provide an inflection point at about 0.065 ppm. Values above 0.1 ppm are weighted at close to their full value, while the very low values are significantly reduced by the weighting scheme. In this way, all ozone readings for a day are included, yet the readings with a greater impact on plant growth (i.e. the peak values) are weighted to reflect their greater impact. The CEI took on values ranging from 10 to 26 ppm-h in the eastern U.S. in 1990.

Regression Results

Table 2 reports results from the corn and soybean yield regressions. White's (1980) heteroskedastic-consistent covariance matrix estimation was used to correct parameter estimates for unknown forms of heteroskadicity. All of the variables had plausible signs and are significant at the ten percent level, with most coefficients being significant at the five and one percent level. The R^2 is not very high (between 0.34 and 0.38) but this is not unusual for cross-sectional models. The coefficients on the *Nitrogen* variable have the expected positive signs, as do *Irrigation and Rotation*. The *Rotation* variable was significant at the ten percent level (two-tailed test) in the corn equation and at the one percent level in the soybean equation, providing some evidence of the importance of rotation strategies for improving yields. The coefficient for *Plant* was negative and highly significant in the corn regression, suggesting a penalty for late planting. The variable *RKLS* measures the erodibility of the soil, with higher values corresponding to greater degrees of erodibility. The results suggest lower yields are obtained on more erodible soils. *Rain* and *Rain*^{2} also have the expected signs, indicating a concave function. The optimal levels of Spring rainfall for the two crops are between 13 and 15 inches. The negative signs on *Hot* and *Cool* indicate that extreme temperatures at either end have negative consequences for yields of both crops.

Table 2. Linear Regression Estimates of Corn and Soybean Yields

	Corn	Soybeans
Nitrogen	0.06	0.04
	(3.76)	(1.65)
RKLS	−0.47	−0.17
	(−2.61)	(−1.82)
Rotation	4.72	3.77
	(1.88)	(4.31)
Irrigation	13.74	6.52
	(2.65)	(2.93)
Plant	−0.33	0.01
	(−4.26)	(1.57)
Rain	27.33	13.05
	(3.90)	(5.33)
Rain^2	−0.90	−0.48
	(−3.45)	(−5.08)
Cool	−17.19	−5.91
	(−3.83)	(−3.67)
Hot	−42.60	−9.52
	(−9.11)	(−7.03)
Ozone	−1.23	−1.02
	(−2.42)	(−5.99)
Constant	−20.51	−32.29
	(−0.44)	(−1.94)
Adj. R^2	0.34	0.38
Log-likelihood function	−2,535.37	−1,693.93

Numbers in parentheses are t-statistics.

The regression equations also provide evidence of the negative impacts of ozone on corn and soybean productivity. Several specifications of ozone-yield response relationships were also tested (quadratic, logarithmic, exponential) in addition to the linear models reported, but none performed as well as the linear models. The elasticities of yields with respect to *Ozone* calculated at the sample means were −0.19 for corn and −0.54 for soybeans. These elasticities are not strictly comparable to those reported in NCLAN studies which are based on 7-hr daily mean exposure measures (Heck, 1989) rather than the W126 measure used here. Lefohn et al. (1988) report experimental results relating soybean yields to the W126 index. For comparable levels of exposure to those in our sample, their yield elasticities are lower, between −0.10 and −0.30. Thus, our farm-level elasticity estimates seem somewhat higher than those derived from experimental data. Leung et al. also found this to be the case in their study of yield-ozone relationships in Southern California. However, our estimates are similar to experimental plot

---

[2] NCLAN studies which include ozone exposures far above and far below ambient levels often report non-linear yield-exposure relationships.

Table 3. Percent of Corn and Soybeans Produced in Counties with High Levels of Exposure to Ozone

	Corn			Soybeans		
	Total Revenues ($ mill.)	% Revenues from Counties with Ozone >12.0 ppm-h	% Revenues from Counties with Ozone >15.0 ppm-h	Total Revenues ($ mill.)	% Revenues from Counties with Ozone >12.0 ppm-h	% Revenues from Counties with Ozone >15.0 ppm-h
Delaware	38.1	100.0	0.0	37.2	100.0	0.0
Maryland	115.7	99.1	90.1	86.8	100.0	93.0
New England	4.7	0.0	0.0	0.0	0.0	0.0
New Jersey	21.4	70.2	32.8	23.0	96.2	64.8
New York	128.8	0.0	0.0	6.0	0.0	0.0
North Carolina	212.6	23.7	16.2	186.3	28.6	20.9
Ohio	934.3	0.0	0.0	792.6	0.0	0.0
Pennsylvania	246.5	38.8	10.2	50.9	44.4	9.4
Virginia	89.4	94.3	54.0	85.0	98.9	64.1
West Virginia	9.3	47.3	34.5	1.4	70.9	64.3
Total	1,800.8	22.4	12.3	1,269.2	24.2	15.3

studies in that soybeans are more sensitive to ozone than is corn (Barse et al., Heck, 1989).

Economic Benefits of Improved Air Quality

Studies estimating the economic benefits from reductions in crop exposure to ozone vary widely in their representations of producer and consumer responses to changes in air quality (see Heck (1989); and Hamilton et al. (1985) for summaries). The simplest, "back of the envelope" approach to estimating benefits is to calculate the increase in the value of output from ozone reduction by multiplying the predicted change in yield by acres and price. This approach has been applied by Shriner et al. (1983), Mulchi (1994), Stanford Research Institute (1981), and by several others cited in Adams et al. (1982). Hamilton et al. refer to this as the "no response approach" because it assumes no change in producer acreage and input decisions or in market prices.

Although it does not generate a true welfare measure, the change in revenue approach is straightforward to apply and requires limited information. Moreover, benefit estimates derived from the revenue approach have been remarkably close to those generated by more sophisticated models which allow, to varying degrees, for producer input and acreage adjustments as well as endogenous price adjustments. Studies by Adams et al., (1982), Leung et al., Brown and Smith, and by Hamilton et al. all report benefit measures derived from the revenue approach to be within 20 percent of measures derived from standard welfare analysis.[3]

In this section, we use this simple revenue approach to estimate the benefits (in terms of value of increased production of corn and soybeans) of a secondary air quality standard for crops based on the W126 cumulative exposure index. The economic benefits of an increasingly stringent standard are calculated. For this analysis, county-level yield and acreage data were taken from the 1992 *Census of Agriculture*, while price data comes from *Agricultural Statistics*[4]. Next, ozone exposure indexes were constructed for each county for 1992. The ozone-yield response functions estimated in the previous section were used to calculate yield increases from a given ozone exposure standard. Yield improvements would only be recorded for counties with ozone levels exceeding a given standard.

The overall economic significance of ozone reduction depends on whether exposures are high in areas of significant crop production. Table 3 shows the levels and percent of corn and soybean production in counties with high exposure levels (defined as more than 12.0 ppm-h) by state for 1992. Less than 22.0 percent of corn production and 25.0 percent of soybean production was in counties with high ozone exposures in 1992. No counties in Ohio, which accounted for 54.8 percent of corn

---

[3] Except for Adams et al. (1982) the studies find that the revenue approach underestimates the benefits of reduced pollution. The revenue approach has the additional limitation of being unable to distinguish between producer and consumer benefits (Adams *et al.*, 1982).

[4] Average state prices were used because county-level price data were not available. It is assumed that intra-state price variation is small.

and 62.2 percent of soybean production in the region, had high exposures. However, ozone exposures were high and pervasive within particular states. Roughly 90 percent of both the corn and soybean crops in Delaware, Maryland and Virginia, 70 percent of the corn crop and over 95 percent of the soybean crop in New Jersey, and over 70 percent of the soybean crop in West Virginia are exposed to ozone levels above 12.0 ppm-h.

Table 4 reports estimates of increased corn and soybean revenues for three hypothetical standards, a summer cumulative exposure index (CEI) of 20.0 ppm-h, 15.0 ppm-h and 12.0 ppm-h, respectively, using 1992 Census of Agriculture data. Corn revenues for the entire region increase by 0.3, 0.7 and 1.3 percent for standards of 20.0, 15.0 and 12.0 ppm-h, respectively. Soybean revenues increase by 0.9, 2.5 and 4.6 percent. Total revenue gains from a 12.0 ppm-h standard are about $82 million, given 1992 base air quality. Significantly, the summer of 1992 experienced relatively low levels of ozone exposure throughout the region.

These results are similar in magnitude to other studies, despite the use of pollution indexes that are not strictly comparable. Dixon et al. (1985) report a 6.5 percent yield decrease for corn and soybeans resulting from an increase in the 7-hr mean ambient ozone exposures from 0.04 to 0.05 ppm. Heck et al. (1984) report yield increases of 1.0 percent for corn and 6.0 percent for soybeans resulting from a 25 percent reduction in ozone exposures.

The benefits of an ozone standard are modest at a regional level, but significant in high exposure areas. Three states, Maryland, North Carolina, and Virginia capture 99 percent of the revenue gains from a 20.0 ppm-h standard and 87 percent of the gains from a 12.0 ppm-h standard. Of the 624 counties in the states considered, there are only 111 (18 percent) where corn is produced and where ozone exposures are above 15.0 ppm-h. In these counties, the revenue gain from reducing ozone exposures to 15.0 ppm-h is $13.5 million in 1992 prices. This amounts to a 6.1 percent increase of total corn revenues in those counties. However, a 15.0 ppm-h standard would increase revenues in the region as a whole by only 0.7 percent. The same is true of soybean production: only 102 counties (16 percent) have both soybean production and ozone exposures above 15.0 ppm-h. The soybean revenue gain from a 15.0 ppm-h standard in high exposure counties is $32.7 million or 16.8 percent of the $194.7 million total soybean crop in those counties. For the eastern U.S. as a whole, a 15.0 ppm-h standard would increase soybean revenues by only 2.5 percent.

Table 4. Estimated Value of Increased Production from Reducing Maximum Ozone Exposures to Selected Levels (millions of 1992 dollars).

Ozone standard (ppm-h):	Corn 20.0	Corn 15.0	Corn 12.0	Soybeans 20.0	Soybeans 15.0	Soybeans 12.0
Delaware	0.0	0.0	1.0	0.0	0.0	3.0
Maryland	2.5	5.4	9.0	4.3	10.0	18.2
New Jersey	0.0	0.0	0.3	0.0	0.1	1.7
North Carolina	0.8	2.9	4.8	3.4	10.9	16.4
Pennsylvania	0.0	0.6	2.4	0.0	0.3	1.4
Virginia	2.0	4.1	6.2	4.5	10.7	17.3
West Virginia	0.1	0.3	0.4	0.1	0.2	0.3
Total	5.4	13.3	24.1	12.3	32.2	58.3

Conclusions

While many studies have estimated the impacts of air pollution on crop yields on experimental plots, few have estimated these impacts under actual farm production conditions. This study econometrically estimates the impact of air pollution on corn and soybean yields, controlling for weather and management practices, using farm-level data for the eastern U.S.. Ozone pollution was found to reduce yields for both crops. The mean elasticities of yield with respect to ozone exposure were -0.19 for corn and -0.54 for soybeans.

The economic impact of alternative secondary ozone exposure standard to protect crops were estimated using the change in revenue method. The region-wide benefits of ozone standards in the eastern U.S. were modest compared to total production values. For cumulative summer ozone exposure standards of 20.0, 15.0, 12.0 ppm-h, regional corn revenues increased by 0.3, 0.7 and 1.3 percent and soybean revenues increased by 0.9, 2.5 and 4.6 percent. Thus, our results are consistent with those based on experimental data which find that ozone reductions have a more significant impact on soybeans than corn. The benefits of standards, measured in terms of crop revenues, range from $17 to $82 million depending on the stringency of the standard.

These benefits accrue mainly to high exposure areas. Three states, Maryland, North Carolina, and Virginia capture over 85 percent of the revenue gains from standards. In counties with ozone exposures over 15.0 ppm-h, a standard reducing maximum exposure to 15.0 ppm-h would increase corn production 6.1 percent (as opposed to 0.7 percent regionally) and soybean production 16.8 percent (as opposed to 2.5 percent regionally).

References

Adams R., T. Crocker, and N. Thanavibulchai. "An Economic Assessment of Air Pollution Damages to Selected Annual Crops in Southern California." *Journal of Environmental Economics and Management* 9(1982):42–58.

Adams, R., S. Hamilton, and B. McCarl. "The Benefits of Pollution Control: The Case of Ozone and U.S. Agriculture." *American Journal of Agricultural Economics* 68(1986):886–93.

Adams, R.M., S.A. Hamilton, and B.A. McCarl, *The economic effects of ozone on agriculture,* EPA-600/3-84-090, U.S. Environmental Protection Agency, Corvallis, Oregon, 1984.

Barse, J.R., W. Ferguson, and V. Whetzel. *Effects of Air Pollution and Acid Rain on Agriculture: An Annotated Bibliography.* Economic Research Service, U.S. Department of Agriculture, Staff Report No. AGES850702, Washington, DC, 1985.

Bilonick, R.A. "Monthly Hydrogen Ion Deposition Maps for the Northeastern U.S. from July 1982 to September 1984." *Atmospheric Environment* 22 (1988):1909–24.

Brown, D. and M. Smith. "Crop Substitution in the Estimation of Economic Benefits Due to Ozone Reduction." *Journal of Environmental Economics and Management* 11(1984): 347–62.

Dixon, B.L., P. Garcia, and J.W. Mjelde. "Primal Versus Dual Methods for Measuring the Impact of Ozone on Cash Grain Farmers," *American Journal of Agricultural Economics* 67(1985):402–6.

Garcia, P., B.L. Dixon, J.W. Mjelde, and R.M. Adams. "Measuring the Benefits of Environmental Change Using a Duality Approach: The Case of Ozone and Illinois Cash Grain Farms." *Journal of Environmental Economics and Management* 13(1986):69–80.

Hamilton, S., B. McCarl, and R. Adams. "The Effect of Aggregate Response Assumptions on Environmental Impact Analysis." *American Journal of Agricultural Economics* 67(1985):407–13.

Hansen, L. "Farmer Response to Changes in Climate: The Case of Corn Production." *Journal of Agricultural Economics Research* 43(1991):18–25.

Heck, W.W. "Assessment of Crop Losses From Air Pollutants in the United States" in J. Mackenzie and M. El-Ashry (eds.) *Air Pollution's Toll on Forests and Crops,* Yale University Press, 1989.

Heck, W.W., W.W. Cure, J.O. Rawlings, L.J. Zaragoza, A.S. Heagle, H.E. Heggestad, R.J. Kohut, L.W. Kress, and P.J. Temple. "Assessing Impacts of Ozone on Agricultural Crops: Crop Yield Functions and Alternative Exposure Statistics." *Journal of the Air Pollution Control Association* 34(1984):810–7.

Heck, W.W., O.C. Taylor, R.M. Adams, G. Bingham, J. Miller, E. Preston, and L. Weinstein. "Assessment of Crop Loss from Ozone." *Journal of the Air Pollution Control Association* 32(1982):353–61.

Heggestad, H.E., and V.M. Lesser. "Effects of Ozone, Sulfur Dioxide, Soil Water Deficit, and Cultivar on Yields of Soybean." *Journal of Environmental Quality* 19(1990): 488–95.

Isaaks, E. and Srivastava, M. *Applied Geostatistics.* Oxford University Press, 1989.

Kopp, R.J., W.J. Vaughn, and M. Hazilla. *Agricultural Sector Benefits Analysis for Ozone: Methods Evaluation and Demonstration.* Raleigh NC: Office of Air Quality Planning and Standards, EPA-450/5-84-003, 1984.

Leduc, S.K., and C.M. Sakamoto. "Regional/National Crop Loss Assessment Modeling Approaches" in *Assessment of Crop Loss From Air Pollutants,* W.W. Heck, O.C. Taylor, and D.T. Tingey (eds.), New York: Elsevier Science Publishing Co., Inc., 1988.

Lee, E.H., D.T. Tingey and W.E. Hogsett. "Evaluation of Ozone Exposure Indices in Exposure-Response Modelling." *Environmental Pollution* 53(1988):43–62.

Lefohn, A.S., C.M. Benkovitz, R.L. Tanner, and L.A. Smith, *Acidic Deposition: State of Science and Technology, Report 7, Air Quality Measurements and Characterizations for Terrestrial Effects Research,* National Acid Precipitation Assessment Program, Washington: U.S. Government Printing Office, 1990.

Lefohn, A.S., "The Characterization of Ambient Ozone Exposures." in *Surface Level Ozone Exposures and their Effects on Vegetation,* A. Lefohn (ed.), Chelsea, MI: Lewis Publishers, 1992.

Lefohn, A.S., J.A. Laurence, and R.J. Kohut. "A Comparison of Indices That Describe the Relationship Between Exposure to Ozone and Reduction in the Yield of Agricultural Crops." *Atmospheric Environment* 22(1988):1229–40.

Lefohn, A.S., and V.C. Runeckles. "Establishing Standards to Protect Vegetation-Ozone Exposure/Dose Considerations." *Atmospheric Environment,* 21(1987):561–68.

Leung, S.K., W. Reed, and S. Geng. "Estimations of Ozone Damage to Selected Crops Grown in Southern California." *Journal of the Air Pollution Control Association* 32(1982):160–64.

Lund, M.G., P.R. Carter and E.S. Oplinger. "Tillage and Crop Rotation Affect Corn, Soybean, and Winter Wheat Yields." *Journal of Production Agriculture* 6(1993):207–13.

Meese, B.G., P.R. Carter, E.S. Oplinger, and J.W. Pendleton. "Corn/Soybean Rotation Effects as Influenced by Tillage, Nitrogen, and Hybrid/Cultivar." *Journal of Production Agriculture* 4(1991):74–80.

Miller, J.E., A.S. Heagle, S.F. Vozzo, R.B. Philbeck, and W.W. Heck. "Effects of Ozone and Water Stress, Separately and in Combination, on Soybean Yield." *Journal of Environmental Quality* 18(1989):330–36.

Mulchi, C. "Estimating the Economic Impact of Air Pollution on Maryland Agriculture." Maryland Institute for Agriculture and Natural Resources, Agricultural Experiment Station, 1994.

Musselman, R., R. Oshima, and R. Gallavan. "Significance of Pollutant Concentration Distribution in the Response of Red Kidney Beans to Ozone." *Journal of the American Society of Horticultural Science* 108(1983):347–51.

Office of Technology Assessment, United States Congress.

Acid Rain and Transported Air Pollutants: Implications for Public Policy, Report OTA-0-204, 1984.

Oshima, R.J., M.P. Poe, P.K. Braegelmann, D.W. Baldwin, and V. Van Way. ''Ozone Dosage-Crop Loss Function for Alfalfa: A Standardized Method for Assessing Crop Losses From Air Pollutants.'' *Journal of the Air Pollution Control Association* 26(1976):861–65.

Shriner, D., W. Cure, A. Heagle, W. Heck, D. Johnson, R. Olsen, and J. Skelly. ''An Analysis of Potential Agriculture and Forestry Impacts of Long-Range Transport of Air Pollutants.'' ORNL-5910 Oakridge National Laboratory, Oakridge, TN, 1983.

Stanford Research Institute. ''An Estimate of the Nonhealth Benefits of Meeting Secondary National Ambient Air Quality Standards.'' Final Report to the National Commission on Air Quality, 1981.

Teigen, L.D., and F. Singer. *Weather in U.S. Agriculture: Monthly Temperature and Precipitation by State and Farm Production Region, 1950–90*. Economic Research Service, U.S. Department of Agriculture, SB-834, 1992.

U.S. Department of Agriculture, Soil Conservation Service and Iowa State Statistical Laboratory. ''Basic Statistics: 1982 National Resources Inventory.'' SB-756, Washington DC, 1989.

Westenbarger, D.A., and G.B. Frisvold. ''Agricultural Exposure to Ozone and Acid Precipitation.'' *Atmospheric Environment* 28(1994):2895–907.