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THE BENEFITS OF PREVENTING CROP LOSS DUE TO TROPOSPHERIC OZONE

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THE BENEFITS OF PREVENTING CROP LOSS DUE TO TROPOSPHERIC OZONE

by

Clive L. Spash

INTRODUCTION

The topic of this paper is ozone smog or tropospheric ozone pollution and the assessment of one aspect of this problem: impacts on agricultural crops. However, the techniques and their problems are applicable to a wide range of impacts from materials damages to human health effects. In addition, the methods explained have been applied to agricultural damages related to both acid deposition (see Adams and McCarl, 1985a) and global climate change (Adams et al., 1988). The concentration here is on the estimation of the tangible benefits from policies to reduce tropospheric ozone concentrations.

TROPOSPHERIC OZONE POLLUTION

Ozone at the tropospheric level (the lowest 10-15 kilometres of the atmosphere) is a separate issue from ozone holes in the upper atmosphere (the stratosphere). All references to ozone here are to tropospheric ozone, unless otherwise stated. While perhaps a less dramatic issue, tropospheric ozone is a well-documented cause of a range of environmental impacts, and is commonly associated with the urban pollution problems of cities such as Los Angeles, Tokyo and Athens. Photochemical oxidants, of which ozone is the most prevalent, are capable of causing plant damage, affecting human health, disrupting ecosystem structures and stability, and reacting with a number of non-biological materials (e.g., rubber), as well as forming a visibility-reducing blue haze. As the most prevalent photochemical oxidant, ozone has been studied extensively and is commonly used as the basis for photochemical oxidant air quality standards.

Injury to plants from photochemical smog was first noted in 1944 when stippling and glazing or bronzing of the leaves of vegetables were discovered in the Los Angeles basin, California.

Tropospheric ozone concentrations alone or in combination with sulphur dioxide and nitrogen dioxide have since been identified as the major source of crop losses caused by air pollution in the United States (Heck et al., 1982). The scientific evidence is growing that both ozone and acid deposition are causing extensive damage to vegetation in both Europe and the U.S. (see MacKenzie and El-Ashry, 1989).

Sources of Ozone

Ozone is formed in the atmosphere from "precursor emissions". Non-methane hydrocarbons, nitrogen dioxide and nitric oxide are the main precursor emissions causing oxidant formation. Naturally occurring, background tropospheric ozone varies seasonally and with latitude, but is normally assumed constant, e.g., 0.025 ppm (parts per million) measured over seven hours of daylight during the growing season (i.e., 7 hours/day seasonal) in U.S. experiments on plant response (Heck et al., 1984). Recognition of the existence of a background level implies a base concentration which policies designed to control anthropogenic sources will leave unaffected.

The basic process of ozone formation is a part of the nitrogen dioxide photolytic cycle. Oxygen atoms (O) are derived principally from the dissociation of nitrogen dioxide (NO_2) by solar radiation: NO_2 + ultra-violet radiation = NO + O. This atomic oxygen reacts rapidly with molecular oxygen (O_2) to form ozone (O_3): $O + O_2 = O_3$. Ozone in turn reacts with nitrogen oxide (NO) to form nitrogen dioxide again: $NO + O_3 = NO_2 + O_2$.

The transportation sector is normally the primary source of anthropogenic ozone precursors. Hydrocarbons released from vehicle exhausts unbalance the naturally occurring nitrogen dioxide cycle by converting nitrogen oxide to nitrogen dioxide without consuming an equivalent amount of ozone. The resulting concentration of ozone varies with temporal variations in precursor emissions (e.g., rush-hour traffic), atmospheric dispersion capacity, and the intensity of solar radiation. The multiple input of pollutants (cumulative loading) as a parcel of air moves across a region can cause downwind (e.g., rural) areas to receive high ozone concentrations absent from upwind (e.g., urban) monitoring stations. For example, there is clear evidence of the effects of such cumulative loading on areas downwind of the London plume (Varey et al., 1980).

Primary and Secondary Standards

The approach to ozone regulation taken by the United States consists of a primary standard designed to protect human health, and a secondary standard to protect other aspects of human welfare (e.g., materials, crops, visibility). The primary standard aims to protect the health of even the most sensitive members of the public with a safety margin. The initial U.S. national ambient air quality standard for ozone was set in 1971 at 0.8 ppm for both standards, not to be exceeded more than one hour per year. Review of the standards in 1979 relaxed both to 0.12 ppm, with the standard not to be exceeded on an average of three days over three consecutive years. While economic information has no role in setting these standards, economists have attempted to measure the social costs of pollution to assess whether a particular standard should be supported. In this respect the relaxation of the ozone standard from 0.08 ppm to 0.12 ppm led to several studies of the economic implications for crop production. In addition, there is good reason to have different primary and secondary standards and to adopt alternative measures of concentration for each, given the different damages society is trying to prevent in each case.

In Europe ozone itself is uncontrolled. This might imply that ozone is either below levels at which damages occur or that current controls of precursor emissions are sufficient. However, the persistence of ozone smogs in cities such as Athens suggests otherwise. The trend towards hot dry summers implied by global warming will increase the concentration of tropospheric ozone from available precursors. In addition, precursor emissions will increase with the volume of traffic, which is rising with both population and car ownership per capita, as well as with sales to the previously unexploited market of the former Eastern bloc. Thus, ozone control is likely to be a policy issue across Europe in the near future.

DEFINING DOSE

The effects of air pollution on vegetation are influenced by biotic, climatic and edaphic (i.e., soil) variables. Inherent genetic resistance has been cited as probably the most important factor influencing plant response to air pollutants. Plant response to ozone varies among species of a given genus (e.g., potato) and varieties or cultivars within a given species (Linzon, et al., 1984).

Ozone, as with other air pollutants, damages a plant after entering the stomatal leaf opening (Holdgate, 1979). Thus, factors affecting stomatal size and opening determine pollutant uptake and the potential for damage. For example, reduced moisture or increased temperature can cause reduced stomatal apertures and higher resistance to air pollution. Plants under no such stresses, growing under favourable conditions, may therefore be more susceptible to damage. In general, plants are better able to cope with exposure to ozone at night (because stomata are closed), and at lower temperatures and relative humidity; they are more susceptible to ozone damage when the leaves are mature, due to the increase in cell gaps

(Medeiros and Moscowitz, 1983).

Farm practices may also alter plant response to air pollution. For example, attempts to improve growing conditions (e.g., irrigation) and reduce plant stress could increase ozone susceptibility. The mixture of production inputs is a factor often ignored in the derivation of dose-response functions under experimental conditions (Adams and Crocker, 1984). Cultural and input variations between regions make dose-response functions which have been derived in one area inappropriate for use in another area. Even when the same inputs and cultivars are used in two different regions, all the other factors would have to concur before a dose-response function derived in one region could be used accurately to predict the yield loss in the second region. This problem is an important criticism of current dose-response methods.

The ambient ozone concentration, the length of time a particular concentration persists and the frequency of occurrences combine to form a measure of the dose of an air pollutant to which a plant is exposed: the "exposure dose". Other characteristics of plant exposure may also be important determinants of the nature and magnitude of the effects of ozone on plants: the length of time between exposures, the time of day of exposure, their sequence and pattern, and the total flux of ozone to the plant as it is affected by canopy characteristics and leaf boundary layers. However, as Table 1 shows, ozone studies into crop productivity have largely defined exposure dose in terms of concentration, duration and frequency to the exclusion of other factors.

Table 1 Details of Ozone Exposure in 23 Studies of Crop Loss

Details Provided	Number of Publications
Concentration	23
Duration	18
Frequency	16
Time between exposures	13
Time of day	6
Fluctuation of concentrations	3
Patterns (sequence)	0
Flux	0

Source: Jacobson (1982) p.298, Table 14.2.

Several types of exposure dose measures have been employed in ozone studies. An extensive project on crop damage due to ozone was conducted by the National Crop Loss Assessment Network (NCLAN) of the United States Environmental Protection Agency (EPA) in the 1980s. NCLAN employed a seasonal seven hour/day mean ozone concentration exposure statistic in all its published dose-response functions. This mean is calculated upon the seven hours judged to be the most susceptible for plants; that is, between 0900 and 1600 hours. The daily means for the seven-hour period are then averaged over the entire growing season, i.e., the period of pollution concentrations relevant to the object being damaged.

The seasonal seven-hour mean statistic combines a large number of ozone concentration observations. However, as Heck et al. (1984) state:

> There is no consensus on an exposure statistic(s) that will best relate to the potential response of plants to varying O_3 concentrations over a growing season. It is generally accepted that the degree of plant response is affected more by differences in concentration than by differences in duration of exposure. Thus a given seasonal mean concentration that includes many high O_3 concentrations could cause greater effects than would the same mean that includes few high O_3 concentrations. This hypothesis is untested for O_3. Possibly no single exposure statistic will be adequate for all crops under all environmental conditions.

The implication is that high ozone concentrations may be lost in the statistic but could be an important explanation of crop loss and therefore need to be taken into account. Thus, NCLAN discussed the use of alternative exposure statistics such as the peak (maximum) daily seven-hour mean ozone concentration occurring during the growing season; the seasonal mean of the daily maximum one-hour mean ozone concentrations; and the peak (maximum) one-hour mean ozone concentration occurring during the season.

The measure of dose used must be compatible with ambient air quality data to enable the development of useful predictive models (Heck et al., 1980). Typically, ozone standards are set where the primary concern is with the threshold for acute damage to human health, and may therefore be inappropriate for dose-response studies. In order to use a different exposure statistic for a standard and a response model, the distribution of ozone in the ambient air needs to provide a basis for using one statistic as a surrogate for another. For example, assume that a seasonal average concentration is discovered at which there is no crop loss, and that this seasonal average is *never* exceeded when a certain hourly peak ozone concentration is not exceeded. Under these circumstances the analyst can reasonably assume that crops are protected when the hourly peak is not exceeded. Unfortunately, the seasonal mean can vary widely, while the peak value remains constant and is unlikely to *always* remain at or below a certain value. The implication for ozone standards is that they should employ concentration measures which relate to chronic, as well as acute, damage.

DERIVING DOSE-RESPONSE FUNCTIONS FOR CROPS

Three main approaches have been employed to derive dose-response relationships for ozone: (a) foliar injury models, (b) secondary response data and (c) experimentation.

(a) Foliar Injury Models

Early studies assumed a threshold below which no damage was presumed to occur and related this to visible, normally foliar, injury. These foliar injury models can be misleading as signs of yield loss because tubers, roots and dry weight, among other factors, can be affected without visible damage. Conversely foliar injury may overestimate damage because some plants can suffer severe leaf damage without loss of photosynthetic ability, and recovery from visible injury can be quick (Leung, et al., 1978). Generally, three types of response to air pollution can be defined; visible injury symptoms, growth responses and quality changes. Foliar injury models ignore "hidden injury" which may occur with the latter two responses. Medeiros and Moscowitz (1983, p.506) note that:

> Hidden injury may include: (1) reduced photosynthetic activity, (2) accumulation of a pollutant or its byproducts within a leaf, (3) an overall unhealthy appearance without necrotic lesions, (4) reduced growth or yield, and (5) increased susceptibility to disease, particularly insect invasion.

Studies with soybeans, tomatoes, annual rye grass, spinach, wheat, lettuce and potatoes have demonstrated that foliar-symptom production is an unreliable index of ozone effects on plant growth or yield (Jacobson, 1982).

(b) Secondary Response Data

Cross-sectional analysis of crop yield data is used to obtain dose-response functions via regression techniques. Information is required on the existing outdoor variations in air pollution, actual crop yields and other environmental factors. Such an approach can save time and money compared to the use of chamber studies under the experimental approach, discussed below.

Leung et al. (1982) obtained statistically significant results for nine crops using this technique; however, the results were sometimes inconsistent when compared to experimental chamber studies, and ozone levels in the study region were high. Rowe and Chestnut (1985) attempted to derive dose-response functions for 10 crops but could only obtain significant results for four of these. They found that the success of the approach was generally dependent upon the effort made to measure and incorporate non-air pollution variables in the yield functions. Generally, their results suggested that ozone was causing yield losses, but the secondary data regression approach captured the effects for only the most sensitive crops, i.e., those which experienced high rates of damage at low ozone levels such as dry beans, cotton, grapes and potatoes.

(c) Experimentation

Several experimental approaches have been developed in studies of ozone effects on crops; these include the use of greenhouses, field chambers (open-top or close-top), unenclosed field plots and the pollution gradient approach. Each approach varies in design or exposure system but, for use in economic assessments, the environmental and exposure conditions occurring on actual farms should be replicated, with only air pollution concentration being modified (Unsworth, 1982). While general responses to ozone of plants grown in different environments may be similar, the quantitative relationships between dose and response are clearly affected by environmental conditions.

RESPONSE FUNCTIONS IN ECONOMIC ASSESSMENTS

Response functions derived from a variety of methodologies have been applied in economic assessments of air pollution damage to agricultural crops. Early work in this area depended upon trained field observers using their judgement to estimate crop damage from visible symptoms (US EPA, 1974). These subjective estimates (often arbitrarily converted into monetary values) were replaced by foliar injury models. In turn, foliar injury models have been found deficient in several aspects, and response functions derived from scientific field experimentation are now commonly applied in economic assessments.

As Table 2 shows for the U.S., 10 out of 15 studies since 1982 have relied upon NCLAN response data, derived from field experiments, as their main source. Of the six studies recently carried out at the national level (for the U.S.), all used the NCLAN data. At the regional level a mixture of data sources is often used. For example, the two studies using secondary data, discussed above, also made use of experimental data for some crops. NCLAN data is a primary source of response information but has so far been restricted to major U.S. agricultural crops. Thus the research of other scientists is employed for important regional crops.

Table 2: Main Source(s) of Response Functions Used in 15 Recent Economic Studies of Ozone Effects on Agriculture

Source of Dose-Response Data		Number of Publications
Experimentation:	NCLAN	10
	Other	3
Secondary		2
Foliar injury		1
Field observation		0

Source: Spash (1987), Table 11.

While the derivation of response functions used in economic assessments has improved, the application of the functions has sometimes been both technically and economically deficient.

Serious errors can arise from extrapolating from a limited data base. For example, the Organization for Economic Cooperation and Development (OECD, 1981) performed a cost-benefit analysis of sulphur oxide which included the benefits expected from crop loss reductions under various scenarios. A dose-yield relationship was developed from information on the response to sulphur dioxide of rye grass (Lolium perenne) and applied to all crops throughout Europe. Barnes et al. (1983) have made the following major criticisms of this study:

(i) It ignored crop and cultivar sensitivities: rye grass is one of the crops most sensitive to sulphur dioxide, resulting in over-estimation of damages.

(ii) It ignored differences in soil sulphur content: the rye grass studies used gave the plant nutritionally adequate supplies, again leading to over-estimation of damage because nutrient-deficient soils actually benefit from sulphur deposition.

(iii) Over-estimation was created by extended extrapolation beyond plant threshold and background pollutant levels, thus creating the illusion of damages when they would be absent or irrelevant to the control of anthropogenic sources.

(iv) The research into rye grass used was mostly from laboratory or greenhouse experiments. This can give results varying widely from plant response to sulphur oxide under field conditions.

This kind of extrapolation and use of response functions ignore the limits of the data base.

The application of one set of results to other crops, cultivars, regions or countries abstracts from variations in plant sensitivity and environmental conditions. However, a certain amount of extrapolation can be justified. In the case of ozone, data are unavailable for many regionally important crops and cultivars; so far, experimental results are largely derived for the major crop-growing regions of the U.S. In the absence of alternative data, "surrogate" response functions have been used for crops judged to be of similar sensitivity. For example, Howitt et al. (1984) studied the economic effects of ozone on 13 crops. They used NCLAN data for 7 crops and derived 5 "surrogate" response functions. Such use of response data relies upon the judgement of researchers and implicitly involves the subjective estimation of uncertainty. This type of probabilistic estimation requires explicit explanation of the areas of uncertainty so that the accuracy of, and possible bias in, the final results are clear.

REGIONAL ECONOMIC ASSESSMENTS OF CROP LOSS

The majority of recent economic assessments of ozone damage to crops have been at the regional level, and these have employed a range economic modelling techniques (Adams et al., 1984b gives a review of some national level studies). The work done in this area before circa 1982 was scientifically orientated and concentrated upon the accuracy of physical estimates of ozone damage to crops. Where monetary values of damages were given, the traditional model was employed without regard for the over-estimation this technique can cause. Published studies have concentrated on two main regions of the U.S.; namely, the Corn Belt (Illinois, Indiana, Iowa, Ohio and Missouri) and California. These areas have a good supply of data on crop response and air quality, and are nationally important crop-growing regions.

A Traditional Study

Linzon et al. (1984) analysed 15 crops grown in two regions of Ontario, Canada. Yield reductions were estimated for each crop using the experimental results of other researchers. No damage was assumed to occur at ozone levels of 0.03 ppm or lower (seven hour seasonal average). The traditional model was used to calculate monetary equivalents of the approximated crop losses. Increased yields, due to pollutant reduction, were multiplied by the current market price to give a producer benefit estimate equal to total revenue; extra production costs were deemed too small for subtraction. The constancy of price assumption was justified (a) by the small magnitude of crop production from the region relative to total market production, and (b) by the existence of supply management and Marketing Boards.

The fact that aggregate supply curves are normally positively sloped was ignored by Linzon et al.; thus the disjointed function of the traditional model was implicitly accepted. As has been discussed, the traditional model seems certain grossly to over-estimate the gain to producers from ozone reductions. This study estimated the average gain to producers of reducing ozone from current levels (the highest regional category being 0.05 ppm, 7hr seasonal mean) to 0.03 ppm as $15 million per annum, with a range of $9 to $23 million (1980 dollars). Five crops accounted for over 80% of the estimate due to their sensitivity to ozone - namely, potatoes, soybeans, tobacco, wheat and white beans.

Quadratic Programming Approaches

Four economic regional studies of ozone crop losses published since 1982 have used the price endogenous QP approach. Three of these were based on the agricultural crop-growing regions of California and employed similar models. The fourth study generated welfare estimates via a micro-macro model, using farm models to derive the effects of regional production changes on national markets.

Adams et al. (1982) studied 14 field crops in four regions of southern California. The dose-response functions are a major weakness of the study, being calculated from foliar injury models which have been converted to reflect yield loss. This approach showed broccoli, cantaloupes, carrots, cauliflower and lettuce to be ozone resistant, with little or no damage occurring. Lettuce in particular seems to be incorrectly classified, with evidence existing which states it to be an ozone sensitive crop. The optimal crop mix after ozone concentrations were reduced showed a very significant decrease in the production of these air pollution tolerant crops, due to their substantially reduced profitability relative to crops that were more sensitive to ozone.

Linear inverse demand functions were assumed for each crop, i.e., price as a function of quantities. The supply functions for all production inputs were assumed to be perfectly price elastic. The Willig approximation conditions were invoked so that any differences between ordinary and compensated consumers' surplus were assumed to be trivial. This invocation was justified because neither income elasticities nor expenditures as a percentage of income seemed likely to be large for the crops being studied.

The model (calibrated to 1976) was set up to maximize the sum of producers' and consumers' surpluses. Reducing ozone levels to 0.08 ppm, the state standard, would have increased 1976 producer quasi-rents by $35.1 million and consumers' surplus by $10.1 million. Production changes induced by altering ozone concentrations were assumed to leave the input mix constant. Changes in ozone concentrations from 1976 levels were reflected by changes in the optimal mix of outputs. Due to the variety of demand price elasticities across crops, the distribution of benefits was a function of the mix of demand curves and resultant crop proportions in the solution. For example, the removal of cotton from the study caused the balance between consumers' and producers' surpluses to be reversed. Cotton has an elastic demand curve, so that the benefits from ozone reduction were largely in terms of a producers' surplus. The exclusion of cotton reduced the producers' gain to $9 million and left the consumers' gain almost unchanged at $10 million.

Although mitigation was allowed for by cross-crop substitution, the authors felt that the use of fixed 1976 production coefficients and resource levels potentially constrained the possible producer mitigative adjustments on the input side. Thus, they warned that the subsequent programming results and welfare effects might be over-estimated. They also suggested, among other things, that improvements could be made by allowing for non zero cross-price elasticities, widening the scope to include effects in other regions and markets and studying a greater variety of crops.

Howitt et al. (1984) studied 13 crops, also in the state of California. They employed the NCLAN experimental results to derive dose-response functions for seven of the crops and other experimental results for one other crop. The remaining five crops were given "surrogate" response functions. The California Agriculture Resources Model (CARM) was used to calculate consumers' and producers' surpluses. This QP model allowed for constrained cross-crop substitution and included 27 other crops which were assumed unaffected by ozone concentrations. The model was similar to that used by Adams et al.

(1982) above but was calibrated to 1978 instead of 1976.

Three ozone scenarios were compared with a base case for 1978. The total welfare gain from a reduction in ambient ozone of approximately 25 per cent (to 0.04 ppm, seasonal seven-hour average) was $35.8 million per annum, and the welfare loss from an increase in ozone levels by approximately 33% (to 0.08 ppm, seasonal seven-hour average) was $157.3 million. (These percentage estimates are given in Adams et al., 1984, p.10.) Reductions in ozone concentrations cause a "downward shift" of the supply function, which is shown graphically as a rotation, i.e., the price intercept remains the same.

Rowe and Chestnut (1985) used the CARM, as utilised by Howitt et al. (1984), to study 16 crops in the San Joaquin Valley, California. Although 33 crops were included in the economic model, only 16 were judged to be affected by ozone or could be supplied with dose-response functions. The study analysed the use of field data regression to derive dose-response functions, but obtained statistically significant results for only four crops: dry beans, cotton, grapes and potatoes. As a result, NCLAN functions were used for six other crops, while a further six were derived from other sources and by the use of "surrogate" functions. Three ozone scenarios were studied (0.12, 0.10 and 0.08 ppm seasonal hourly maximum) and results were given for both consumers and producers. Sulphur dioxide was also included in the study, but over 98% of the economic value of the agricultural damages was attributed to ozone. If an ozone standard at which little or no crop damage was expected (defined as 0.08 ppm seasonal hourly maximum) had been met in 1978, the estimated gain to consumers would have been $30.3 million and the gain to producers $87.1 million.

Adams and McCarl (1985b) studied three crops in the Corn Belt region of the U.S. with a QP model calibrated to 1980. The dose-response functions were taken from NCLAN results for 1980-1982 and were Illinois specific. The model analysed the changes occurring throughout the agricultural sector at the national level as a result of the adjustments in Corn Belt output, *ceteris paribus*. This was achieved by characterizing regional agricultural production using 12 representative farm models. These representative farms were then used to generate supply adjustments in the national level model. Consumers' and producers' surpluses were calculated under two scenarios. An improvement in air quality of 25% (a reduction of ozone from 0.12 ppm to 0.08 ppm one hour seasonal average) gave total benefits of $688 million (1980), a loss to producers of $1,411 million and a gain to consumers of $2,079 million. The other scenario took a 50% degradation in air quality (an increase in ozone from 0.12 ppm to 0.16 ppm one hour seasonal average) and gave a total loss of benefits of $2,225 million, a reduction of consumers' surplus by $4,986 million and an increase of producers' surplus by $2,761 million. Increases in crop supply were found to favour consumers while reductions in crop supply favoured producers. These distributional consequences are a result of supply shifts in the face of a price inelastic demand curve. That is, output increases but farmers lose out as the price falls by a relatively large amount.

Econometric Approaches

Several econometric approaches have been applied to the assessment of crop damage due to ozone pollution, including a dual model. First a model which analyses producers' surplus changes is discussed. Published research shows variation between models, for example concerning assumptions about the nature of agricultural crop supply curves and production responses (see Leung et al., 1982; Page et al., 1982; and Spash, 1987).

Benson et al. (1982) studied four crops in Minnesota. Originally, six crops were to have been studied but since dose-response functions could not be calculated for soybeans and oats, they were dropped. Dose-response for the four remaining crops was calculated using experimental data reported by other researchers. The dose-response functions allowed for episodic (as opposed to chronic or acute) exposure by breaking the exposure into multiple time periods over the growing season. The functions were applied to Minnesota using actual or simulated county-level ozone data. This was used to derive a range of yield losses under different ozone concentrations.

The economic analysis, using a comprehensive econometric model of U.S. agriculture, was carried out under two separate conditions: (a) crop loss was restricted to Minnesota alone, and Minnesota and U.S. production levels were estimated; (b) the same rate of loss as occurred in Minnesota was assumed to occur over the entire U.S., and again Minnesota and national production levels were estimated. A range of producer welfare estimates was derived, with the worst case ozone level (0.12 ppm hourly concentration with ten occurrences per week) causing a *loss* of $30,366,409 under assumption (a) compared to 1980 production. The worst case estimate under assumption (b) gave a *gain* to producers of $67,540,745 compared to 1980 production.

The explanation for the gain under (b) is that price rises as output is restricted and the "price effect" dominates, whereas under (a) the "production effect" dominates. The increase in the total value of production as ozone increases is due to the price inelastic nature of demand for the commodities studied. This "gain" to producers is in fact misleading in that: (1) costs have risen due to ozone pollution, and so a loss of comparative advantage is suffered by all affected farmers (the gain is at best a short-run phenomenon as competition from other sources would drive high-cost producers out of the industry; as the authors note, scenario (a) is more likely in the long run). (2) focusing on the "gain" to producers ignores the dynamics of consumer and producer welfare. Benson et al. do not calculate consumers' surplus; therefore the net change in societal welfare and the distribution of welfare changes, are unknown. In addition, scenario (b) is highly dubious because of the assumption that regional dose-response/ozone estimates can be extrapolated to the national level.

Although a detailed national-level model was used, Benson's economic analysis is similar to that of the traditional model. A comprehensive econometric model of the U.S. agricultural sector (calibrated to 1980) was used to capture crop supply and demand across multiple domestic and foreign markets. Despite accounting for national-level changes, the regional model remains simplistic in that quantity is being multiplied by price in order to estimate the "value" of production (namely producer quasi-rents). Also, cross-crop substitution is ignored as a mitigative strategy.

A Duality Study

Mjelde et al. (1984) employed the neo-classical econometric model with a profit function. Duality models are not dependent on an explicit dose-response function to estimate the welfare changes from a change in crop yield. However, experimental data are required to frame the initial hypothesis and to cross-check the resulting estimates. The profit function, which includes ordinary economic variables and environmental variables (as fixed inputs), shows the effects of varying ozone concentrations on farm profits.

Pollution, which is deleterious to the production process, will exert an exogenous force upon producer decisions. Producers may respond by varying input mixes, even if they are unaware of the phenomenon causing the observed effects. As Dixon et al. (1985, p.404) state:

> A profit function that has air quality as an input can be used directly to determine the producer's loss in profit and how other inputs are adjusted in response to a change in air quality. A dose-response function, while useful in establishing cause and effect relationships, does not provide this latter type of information. Furthermore, the change in the supply of a crop can be computed directly and this response is the net effect in agricultural output, i.e., the response incorporates producer adjustments triggered by price yield effects.

Part of this theoretical advantage may be lost in the case of ozone as producer adjustments should exclude a change of input mix. In order to compare the results of a dual study with experimental results, such as those of NCLAN, the mix of variable inputs is assumed constant. However, producers may adjust their output mix, but are prevented from doing so in this study.

The study analysed three crops in Illinois. Detailed farm level cost and production information was made available by the Illinois Association of Farm Business Farm Management which provided a rich source of individual farmer data unavailable in many other states. The study found that increased ozone levels depressed output and reduced the marginal productivity of variable inputs so that less were used. Ozone resulted in an aggregate loss in profits to Illinois farmers of approximately $50 million (1980). The assumption of a constant price ignores consumers' surplus and may be unjustified because Illinois is a major grain producer. Also, if ozone reduction improved crop yields throughout the Corn Belt, both consumers and producers would be expected to benefit. As the study states (Mjelde et al., 1984, p.361):

These loss figures should be interpreted with extreme caution. They are computed under the assumption that price remains constant. Such an assumption is not valid if ambient ozone levels increased in other grain producing regions. If this latter case occurs then the supply curve of feed grains would shift to the left. Given an inelastic demand curve (which is typical of demand in the short run), the corresponding price rise may leave producers better off than before the ozone increase. However, consumers would be worse off than before. This illustrates the importance of analyzing both producer and consumer interactions in drawing conclusions about the impact of any pervasive environmental change.

ECONOMICALLY IMPORTANT ASPECTS OF RESPONSE FUNCTIONS

In performing an economic assessment of crop loss, the response changes of interest are those related to both the costs of production and the marketability of a product (Adams et al., 1985). That is, there are two routes via which pollution-induced crop damage can influence the welfare of consumers and producers. First, a reduction in crop damage, expressed as an increase in yield, will reduce costs and therefore reduce the minimum price the producer must receive to supply a given quantity. Secondly, altered levels of air pollution may affect the attributes of a crop, thus changing the consumer's willingness to pay and the welfare derived from the consumption of a given quantity of a crop. The change in cost implies a supply response, while the change in quality a demand response.

Studies conducted on ozone crop damage have tended to concentrate upon yield, and therefore are only relevant to the supply response. Research into potential crop quality changes has received little emphasis. Yet there is evidence that such quality changes do result from ozone pollution. Examples of quality changes which have been found are shrivelling in kernels of corn, reduction in the size of tomatoes, and alterations in chemical composition that affect cooking quality of potatoes and nutritional values of alfalfa (Jacobson, 1982). Table 3 clearly shows that there is a wide range of possible crop responses to ozone. Research is required to estimate the importance of these responses. This may be a difficult problem to resolve where consumer tastes are concerned, requiring objective characteristics to be associated with economic values in order to allow the derivation of dose-response functions appropriate for economic benefit assessments. However, without work in this area, economic assessments cannot be made of the full range of possible economic impacts.

Table 3: Processes and Characteristics of Crop Plants that may be Affected by Ozone

Growth	Development	Yield	Quality
Rate	Fruit set & development	Number	Appearance: size, shape, colour
Pattern	Branching	Mass	Storage life
	Flowering		Texture/cooking quality
			Nutrient content
			Viability of seeds

Source: Jacobson (1982), p.296, Table 14.1.

CONCLUSIONS

In this paper I have concentrated on benefit estimation without comparison with the costs. Costs will vary depending upon the policy approach and are over-estimated by the inevitable reduction of other intangible damages and other forms of pollution due to ozone precursors, such as acid deposition. A particularly efficient way of controlling ozone for threshold damages could be to avoid high concentrations by enforcing episodic controls e.g., restrictions on vehicle use associated with ozone levels. In the case of Chicago episode regulation has been estimated at $12.9 million (in 1978 dollars; Cohen and Macal, 1981). Four stages of episode are defined: advisory 0.07 ppm, yellow alert 0.17 ppm, red alert 0.30 ppm and emergency 0.5 ppm. The frequencies of occurrence were 60, 4, 0.5 and 0.056 days per year respectively. The temptation to transfer such estimates to other regions should be avoided as the cost of control varies with specific concentrations, e.g., 1hr/day annual (to prevent human health effects) versus 7hr/day seasonal mean (to prevent crop damages); it is also highly region specific due to meteorological conditions.

The dose which a particular crop will receive in a given growing season is a function of precursor emission levels, as well as of meteorological, climatological and topographical factors. When certain meterological conditions prevail, high ozone concentrations may result. The highest ozone levels occur during the spring and summer months coinciding with the growing season for many agricultural crops.

Crop damage is a function of the ozone dose, crop species and cultivar, and biological, climatic, edaphic, production and other factors. The interaction of these variables makes accurate crop loss assessment, especially over large areas, an error prone task. Results from field experiments, especially those of NCLAN, have increased the accuracy with which the economic consequences of plant damage caused by ozone can be estimated. Where crop or region specific information is lacking, qualified approximations to actual responses can be made using surrogate functions. Current economic assessments of crop loss from ozone are restricted by a lack of information as to the importance of crop quality responses and must therefore concentrate upon supply response alone.

Several methodologies are available for crop loss assessment and have been applied to the analysis of welfare changes due to alterations in ozone pollution levels. Among these the microtheoretic econometric models provide a theoretically rigorous structure and have become a common approach to studying the agricultural sector. In conceptualizing agricultural crop production changes, neutral factor productivity enhancement is unanimously accepted (i.e. no input is favoured or harmed more than any other by ozone concentrations), while output substitution will depend upon particular circumstances. Demand functions must be estimated if credible welfare measures are to be obtained. Finally, the supply function characteristics used in recent studies have not been fully explained and may cause unjustified bias in benefit estimates.

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