Journal of Environmental Management (1999) **55**, 273–289
Article No. jema.1999.0256, available online at http://www.idealibrary.com on IDEAL®

The cost of crop damage caused by ozone air pollution from motor vehicles

J. J. Murphy†*, M. A. Delucchi‡, D. R. McCubbin¶ and H. J. Kim§

The effects of ozone air pollution on the agricultural sector are an important environmental challenge facing policy makers. Most studies of the economic impact of air pollution on agriculture have found that a 25% reduction in ambient ozone would provide benefits of at least $1–2 billion annually in the United States. This paper extends existing research by estimating the benefits of a reduction in emissions from a major source of ozone formation: motor-vehicle emissions. An agricultural production model is combined with an analysis of motor-vehicle emissions and air quality to estimate the impacts of emissions from six different motor-vehicle classes, at both the regional and national level. The benefits to the agricultural sector from completely eliminating ozone precursor emissions from motor vehicles ranges between $3·5 and $6·1 billion annually.

Keywords: economics, air pollution, environmental policy, motor-vehicle emissions, agricultural production.

**Corresponding author*

†Economic Science Laboratory, University of Arizona, Tucson, AZ 85721, USA and Department of Agricultural and Resource Economics, University of California at Davis, Davis, CA 95616, USA

‡ Institute of Transportation Studies, University of California at Davis, Davis, California 95616, USA

¶ Department of Economics, University of California at San Diego, La Jolla, California 92093, USA

§ Environmental Economics Division, Office of Policy, US Environmental Protection Agency, Washington, DC 20460, USA

Received 26 November 1997; accepted 23 July 1998

Introduction

The detrimental effects of ambient ozone on crops, even at relatively low concentrations, are well established (Heck and Brandt, 1977; Heck *et al.*, 1982; California Air Resources Board, 1987; Olszyk *et al.*, 1988a, 1988b; Ashmore, 1991). Ozone enters plant leaves through the stomatal openings in the leaf surface and then produces byproducts that reduce the efficiency of photosynthesis. Research suggests that ozone, either alone or in combination with nitrogen dioxide and sulfur dioxide, may be responsible for up to 90% of US crop losses resulting from air pollution (Heck *et al.*, 1982). In an effort to address this problem, the Clean Air Act and its amendments include air pollution damages to vegetation as one of the criteria by which secondary national ambient air quality standards are evaluated (Adams *et al.*, 1984).

There is, of course, an economic cost associated with this reduced productivity. The cost of crop damage due to all anthropogenic ozone air pollution is measured as the gain in welfare that would result if all anthropogenic emissions were eliminated. Thus, the cost is the benefit foregone, i.e. the benefit that would be realised if the emissions were eliminated. In this sense, 'cost of pollution', 'pollution damage' and 'benefit of reducing pollution' are interchangeable in this paper. An updated and improved estimate of the national and regional cost of crop damage due to ozone air pollution, and an original estimate of the crop damage cost of emissions from motor vehicles are presented. An agricultural production model is combined with estimates of motor-vehicle emissions and ambient air quality to estimate the change in consumer and producer welfare resulting from a 100% reduction in all anthropogenic emissions of ozone precursors, and from a 10% and a 100% reduction in emissions of ozone precursors from six different classes of motor vehicles. We focus on motor vehicles because they are one of the largest and most intensively regulated sources of ozone precursor emissions (Davis, 1997), and because

0301–4797/99/040273+17 $30.00/0

of the growing general interest in analyses of the full social costs of motor-vehicle use (e.g. Murphy and Delucchi, 1998). Our analysis is limited to the continental United States and to the year 1990.

Previous research

Over the last 15 years, there have been many studies of the economic effects of reduced agricultural production due to ozone air pollution (see Delucchi *et al.*, 1996, and especially Spash, 1997, for summaries). However, most of the studies estimate regional impacts (Adams *et al.*, 1982; Brown and Smith, 1984; Howitt *et al.*, 1984; Energy and Resource Consultants, 1985; Adams and McCarl, 1985; Mjelde *et al.*, 1984; Rowe and Chestnut, 1985; Howitt and Goodman, 1989); only a few have developed national models (Kopp *et al.*, 1985; Adams *et al.*, 1986; Adams *et al.*, 1989). The national studies generally have found that a 25% reduction in ambient ozone would provide benefits of at least 1–2 billion dollars annually in the United States (see the summary in Adams and Crocker, 1989). In this paper, results are presented for 12 regions of the US, and for the nation as a whole. For a comprehensive literature review see Spash (1997).

All of the aforementioned studies estimate crop damages due to ambient pollution from all sources; none estimates the damages and costs due to motor-vehicle air pollution alone. In addition to estimating the agricultural cost of all anthropogenic air pollution, we also use an emissions-allocation model, discussed in Delucchi and McCubbin (1996), to isolate the contribution of motor-vehicles to overall ozone air quality. The increase in crop output and consumer and producer welfare is then estimated for a 10% reduction and a 100% reduction in emissions of ozone precursors due to motor-vehicle use in 1990, and these costs are allocated to six different classes of motor vehicles.

The model

Overview

The net agricultural benefits of three pollution-reduction scenarios are modeled in the continental United States:

- *Case I* Eliminate 100% of anthropogenic emissions of ozone precursors;
- *Case IIA* Eliminate 10% of motor-vehicle related emissions of ozone precursors;
- *Case IIB* Eliminate 100% of motor-vehicle related emissions of ozone precursors.

It is emphasised that we are modeling the benefits due to the elimination of ozone *precursors*, specifically, VOC and NO_x emissions. A summary of the estimation procedure follows; details are provided in Delucchi *et al.* (1996). A model of agricultural production and demand is used to estimate the welfare changes due to ozone air pollution the markets for eight major crops (see the next subsection). We will refer to this agricultural optimisation model for eight major crops as the AOM8. The AOM8 is used to generate estimates of the change in producer surplus for each of 12 agricultural production regions defined in Table 1, as well as an estimate of the change in consumer surplus. This calculation is done for actual ozone levels in 1990, for ozone at the natural background level (Case I), and for ozone at the level it would be if motor-vehicle-related emissions of ozone precursors were reduced by 10% (Case IIA) and by 100% (Case IIB).[1] The effects of a decrease in ozone are modeled as a shift in the production function—at lower ozone levels, more output is obtained from a given set of inputs. We use yield-loss (or dose-response) functions and values of production to scale these estimated welfare changes to account for ozone damages to other crops not include in the AOM8 and apply a simple scaling factor to account for damages from pollutants other than ozone. The shift in the production function is estimated based on dose-response functions for crops. The ozone data needed for the dose-response functions are either actual ozone readings in 1990, or modeled ozone levels assuming reductions in anthropogenic or motor-vehicle related emissions. The costs were allocated to six different classes of motor-vehicles based on emissions of NO_x and VOC emissions from each vehicle class.

[1] The natural background level is the ozone concentration without man-made sources. It averages between 0·04 and 0·045 ppm for 1 h or an 8 h average between 0·025 and 0·027 ppm (USEPA, 1996).

Table 1. Agricultural production regions in the optimization model (AOM8)

Regions	States
North-east	Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, New York, Pennsylvania, Maryland, Delaware, New Jersey
Lake States	Minnesota, Wisconsin, Michigan
Corn Belt	Iowa, Missouri, Illinois, Indiana, Ohio
Appalachian	Virginia, West Virginia, Kentucky, Tennessee, North Carolina
South-east	Florida, South Carolina, Georgia, Alabama
Delta States	Mississippi, Arkansas, Louisiana
Southern Plains	Texas, Oklahoma
Northern Plains	North Dakota, South Dakota, Nebraska, Kansas
Mountain-I	Colorado, Idaho, Montana, Utah, Wyoming
Mountain-II	Arizona, Nevada, New Mexico
Pacific-I	Oregon, Washington
Pacific-II	California

The welfare effects of changes in agricultural production in the markets for the eight major crops included in the AOM8

The model of agricultural production and demand (AOM8) is a modified version of the model in Howitt (1991). The AOM8 is a self-calibrating, non-linear optimisation program that accounts for both endogenous price effects and the substitution of cropping activities in response to changes in output or input prices.

An advantage of this model over other national production models that use mathematical programing techniques is its ability to calibrate precisely to empirical data. In general, the model allows farmers to re-optimise their total agricultural production in response to ozone air pollution, subject to regional limits on resources, and calculates the change in consumer and producer surplus with respect to this adjusted optimum. The model calibrates precisely, yet can respond to changes in the competitive equilibrium that are induced by policy or resource changes. Of the 238 production activities in the model, only two calibrated with an error greater than 1% from the base year input quantities. This was due to the low input levels of these two activities relative to the other crops in the region (Howitt, 1991).

The AOM8 includes eight major crops, which in 1990 accounted for 63% of the total value of agricultural production in the United States (see Table 2). The agricultural production data used in the model were from Bureau of the Census (1989). For each crop and region, these data include output prices, average yields, input costs and input use for both dry and irrigated acreage, and for acreage both enrolled and not enrolled in the price support program. The data do not distinguish between production for export vs. domestic consumption. These data are reported every 5 years at the county level; at the time that the model was calibrated, the 1987 data were the most recent available. To estimate the agricultural production data for 1990, we scaled the 1987 county-level crop-production data by the ratio of total national production in 1990 to total national production in 1987, for each crop. (This assumes that from 1987 to 1990, production changed by the same factor, the national average, in every county).

The social benefit of a reduction in ozone air pollution is equal to the change in producer surplus, plus the change in consumer surplus, less changes in deficiency payments, which are simply a transfer and therefore do not affect social welfare.[2] The welfare change in

[2] Deficiency payments were the result of a voluntary federal crop price support program that guaranteed growers a minimum price for all acreage enrolled in the program. If the market price fell below a target price, these payments were the difference between the target price and the actual market price. This program no longer exists, but it was in effect during 1990, the year of our analysis.

Table 2. 1990 value of production for crops included in the analysis (billions of 1990 dollars)

Crops	Major Production States (in order of value of production)	Value of Production[a] ($Bil)	Ave O_3 (ppm)[b] low	high
Eight major crops in the AOM8				
Corn	Iowa, Illinois, Nebraska	18·2	0·038	0·044
Soybeans	Illinois, Iowa, Indiana	11·0	0·044	0·048
Wheat	Kansas, North Dakota, Montana	7·2	0·041	0·044
Alfalfa Hay	Wisconsin, California, Iowa	6·6	0·040	0·046
Cotton	Texas, California, Mississippi	5·1	0·049	0·055
Grain Sorghum	Kansas, Texas, Nebraska	1·2	0·043	0·046
Rice	Arkansas, California, Louisiana	1·0	0·050	0·056
Barley	North Dakota, Montana, Idaho	0·9	0·040	0·044
Subtotal—8 crops		*51·2*	–	–
Ten most valuable crops not in the AOM8				
Tobacco	North Carolina, Kentucky, Tennessee	2·8	0·043	0·047
Potatoes	Idaho, Washington, California	2·4	0·045	0·049
Grapes	California	1·7	0·053	0·056
Tomatoes	California, Florida	1·6	0·051	0·057
Oranges	Florida, California	1·5	0·042	0·046
Apples	Washington, New York, California	1·4	0·040	0·048
Sugarbeets	Minnesota, Idaho, California	1·2	0·044	0·048
Peanuts	Georgia, Texas, North Carolina	1·2	0·048	0·052
Lettuce	California, Arizona	1·1	0·058	0·062
Sugarcane	Florida, Hawaii, Louisiana	0·9	0·042	0·045
Subtotal 10 crops		*15·8*	–	–
All other crops	California, Florida	13·8	0·044	0·050
All crops		*80·8*	–	–

[a] From the National Agricultural Statistics Service (1995a–d) and USDA (1992).
[b] This is roughly the production-weighted national-average Kriged rural ozone air quality for each crop, in 1985/1986. Note that this is the air quality estimated for scaling the AOM8 results to account for damages to crops *not* in the AOM8; this is not the air quality estimated for use in the AOM8.

the markets was estimated for the eight major crops for each of 12 regions of the United States. The competitive equilibrium, which maximises social welfare, can be formally defined by maximising the sum of producer and consumer surplus; this is identical to maximising the area under the demand curves, less production costs (net of deficiency payments), subject to regional resource constraints (see Delucchi *et al.*, 1996, for complete model specification).

In addition to variable input costs, the model also includes hedonic program costs and regional marketing costs. Hedonic program costs reflect the implicit costs of enrolling in the crop price support program. Given that this program offers growers a higher expected price and lower risk, the only explanation for partial enrolment of acreage in the program must be that the growers have, or act as if they have, a cost of being enrolled in the program which increases with the acreage enrolled (Howitt, 1991). Regional marketing costs account for the differences in regional prices, which generally arise from differences in marketing and transportation costs.

Our estimate of the welfare impact of air pollution is based on the estimated difference between actual 1990 crop production, and what crop production would have been given various reductions in emissions of ozone precursors. Actual 1990 regional output, Q_{ir}^{90}, is defined by a Cobb-Douglas production function with land, water, capital, nitrogen and pesticides as inputs. Shifts in the production function due to the reductions in ozone are modeled as:

$$Q_{ir}^{90'} = (1 + \frac{QGAIN\%_{ir}}{100}) \cdot Q_{ir}^{90} \quad (1)$$

where $QGAIN\%_{ir}$ is the percentage change in yield of crop i in region r resulting from a reduction in ambient ozone concentrations from initial ozone levels (superscript 90) to ozone levels after either all anthropogenic ozone precursors are eliminated (Case I), or a 10% or a 100% reduction of emissions from motor vehicles (Cases IIA and IIB). These are denoted by the superscript 90′. This specification assumes that for any crop, a given change in ozone causes a constant percentage change in output for any combination of inputs. Thus, we shift the original production function by the percentage change in output corresponding to the estimated change in ozone. The percentage change in output resulting from a change in ozone, i.e. the parameter *QGAIN*%, is calculated from dose-response functions, which are discussed in a later section. Each of the four production conditions (Q_{ir}^{90} for the initial ozone levels, and $Q_{ir}^{90'}$ for the three ozone reduction scenarios: I, IIA and IIB) result in a separate and unique set of optimal resource inputs, equilibrium prices and quantities, and producer and consumer surplus measures.

To estimate equilibrium prices and quantities, the AOM8 includes a linear demand curve for each crop. These national (not regional) demand curves are calculated based on estimates of the elasticity of national demand for each crop in the base year, a weighted-average national baseline price for each crop, and the aggregate national baseline quantity for each crop (Howitt, 1991).[3] Three points are important here. First, these baseline national aggregated prices and quantities are only used to estimate the parameters of the individual crop demand functions; they are not the same as the estimated equilibrium values from the optimisation model. Second, we use national demand functions, not regional, because the demand elasticities were not available at the regional level. Third, ozone pollution changes the level of consumption through a shift in supply, but does not affect the demand curve *per se*, which is independent of the pollution levels. Hence, we use the one set of demand equations for all ozone levels.

[3] Because we have aggregate national demand functions, we cannot estimate the regional changes in consumer welfare.

Accounting for ozone damages to crops not included in the AOM8, and damages from other pollutants

In order to have a complete estimate of air pollution damages to agriculture, we must estimate ozone damages to crops other than the eight in the AOM8, as well as the damages to all crops from other pollutants. Because many of the crops *not* included in the AOM8 are exposed to at least as much ozone, and are at least as sensitive to ozone, as are the eight crops included in the AOM8, we cannot ignore ozone damages to them. Hence, we also estimate the ozone damages to all of the crops *not* included in the AOM8 based on their ozone sensitivity, ozone exposure and value of production relative to that of the eight crops included in AOM8. We do this for each of the ten most valuable crops *not* included in the AOM8, and for the category ‘all remaining crops’.

In general, the welfare effect of air pollution is a function of the value of crop production, the ozone sensitivity of the crops, the exposure to ozone, the elasticity of demand for the crops and the constrained ability of producers to reallocate resources to less sensitive crops. The value of crop production, ozone sensitivity and ozone exposure are comparatively simple to represent, for any crop, but the supply and demand effects are more complex and require a more formal model, such as the AOM8. For the crops *not* included in the AOM8, we can estimate the value of production, the sensitivity to ozone, and the exposure to ozone, but we cannot formally model the optimal adjustment of the crop markets to the effects of ozone on output.

Without a formal model of the market for the crops other than the eight in the AOM8, we are unable to formally estimate two pieces of the welfare change due to ozone air pollution: the consumer surplus associated with the lost (ozone-damaged) output, and the mitigation of the output loss due to producers’ reallocation of resources to less sensitive crops. Put another way, a simple estimate of ozone damages as equal to the loss of market value—the price of the crop multiplied by the quantity lost due to ozone—fails to capture consumer value in excess of the price, but also fails to allow for the mitigating effects of producer reallocation of resources.

The failure to capture consumer surplus causes the simple method to underestimate the true welfare cost, but the failure to allow for the mitigating effects of producer reallocation of resources causes the simple method to overestimate the true welfare cost. It turns out that, in our high-cost case, these two effects cancel: for the eight major crops included in the AOM8, the simple 'lost-market-value' estimate of the cost of ozone air pollution is the same as the detailed formal estimate based on the AOM8. However, in the low-cost case, the AOM8 estimate is 23% higher than the simple estimate, for the eight crops in the AOM8.

In light of this, we have two choices regarding the combined effect of consumer surplus and producer reallocation in the markets for the crops *not* in the AOM8: (1) ignore them, in the hope that they cancel; or (2) make some simple assumption about how they might affect the simple estimates of lost market value. We have chosen the latter. Specifically, we assume that in the market for the crops *not* in the AOM8, the ratio of the true welfare change (as would be calculated if we were able to incorporate these crops into the AOM8) to the simple change in market value is the same as that for the eight major crops included in the AOM8. This means that to get an estimate of the effect of ozone in *all* crop markets, we can simply scale the welfare change calculated with the AOM8 for the eight crops by the ratio of the simple change in market value for *all* crops (the eight in the AOM8, plus all others) to the simple change in market value for the eight crops. Formally:

$$\Delta TW_{USA} = \Delta W_{USA8} \cdot \left(1 + \frac{YLV_{OC}}{YLV_{8C}}\right) \cdot SFOP$$
$$YLV_{OC} = \sum_{o} VP_{o} \cdot \frac{Q_{o,PP}}{Q_{o,PI}} \quad (2)$$
$$YLV_{8C} = \sum_{i} VP_{i} \cdot \frac{Q_{i,PP}}{Q_{i,PI}}$$

where ΔTW_{USA} is the total change in economic welfare in the markets for all crops due to a reduction in ambient pollutant concentrations from 1990 levels to background levels; ΔW_{USA8} is the increase in total economic welfare in the markets for the eight major crops due to a reduction in ambient ozone concentrations from 1990 levels *o* to background levels (Case I) or levels without 10 or 100% of motor-vehicle related ozone precursor emissions (Cases IIA and IIB); *YLV* is the yield-loss value of ozone damage to crops; *VP* is the value of crop production in 1990 (Table 2, column 3); *SFOP* is the scaling factor to account for damages from pollutants other than ozone (estimated to be 1·05–1·10; see below); Q_{PP} is the yield loss function for background ozone levels *PP*; Q_{PI} is the yield-loss function for initial ozone levels *PI* in 1990; subscript *OC* denotes crops other than the eight included in the AOM8; subscript *8C* denotes the eight crops included in the AOM8; subscript *o* denotes those crops *not* included in the AOM8; and subscript *i* denotes the crops included in the AOM8.

The yield-loss functions require an estimate of the ambient ozone air quality in the regions where the crops are produced (see the next subsection). Note that ozone air quality tends to be worse in the growing regions of California (where many of the non-AOM8 crops are grown) than in most other parts of the country—certainly, worse than in the growing regions of the Midwest (where most of the AOM8 crops are grown). The upshot of this is that the production-value weighted ozone air quality for the crops included in AOM8 probably is close to that of agricultural areas of Illinois, whereas the production-value weighted ozone air quality for the crops not included probably is closer to the average in agricultural areas of California.

Gaseous sulfur dioxide (SO_2) and nitrogen dioxide (NO_2), alone or in concert with ozone, and the resultant sulfate and nitrate acid deposition, may also cause minor amounts of damage to some plants. In the NCLAN, only two of the crops, soybeans and tomatoes, showed statistically significant responses to SO_2, and in only one experiment, involving cotton in Raleigh in 1982, did SO_2 significantly affect the response of cotton to ozone (Lesser *et al.*, 1990). Spash (1997) reports that the NCLAN found 'no significant decrease in crop yields from SO_2 or SO_2/O_3 interactions' (p. 65). Similarly, in the National Acid Precipitation Assessment Program (NAPAP), gaseous SO_2 and NO_2 had a negligible impact on crops in the United States (Herrick and Kulp, 1987).

Barley, clover and lucerne are especially sensitive to SO_2 (Ashmore, 1991). However, clover and lucerne are minor crops. Moreover, SO_2 can also stimulate growth, for example by overcoming a deficiency in soil sulfur (Ashmore, 1991). Energy and Resource Consultants (1985) report studies showing that SO_2 causes reductions in yield of alfalfa, tomatoes, potatoes and dry beans. However, in their study of the economic effects of air pollution on crops in California's San Joaquin valley, SO_2 levels were high enough to affect potatoes only, and as a result, damages from SO_2 were only 2% of the total, the rest being damage from ozone (Energy and Resource Consultants, 1985; Rowe and Chestnut, 1985).

The effect of acid precipitation also appears to be minor. The NAPAP performed field studies of 13 varieties of 8 important crops, and mechanistic and screening experiments involving other grains (5 species), vegetables (14 species), fruits and nuts (4 species) and other crops (11 species), and concluded that acid deposition had a negligible effect on crops in the US (Herrick and Kulp, 1987). Adams *et al.* (1986) estimated that a 10–50% increase in acid deposition would cost $19–$140 million (1980 dollars) in losses in the market for soybeans, the only crop found to be sensitive to acid deposition (also see Spash, 1997). This is more than an order of magnitude smaller than their estimate of the impact of a 25% change in ozone. Moreover, when Adams *et al.* (1986) included fertilisation effects—additional expense for lime, to reduce acidity, but less expense for nitrogen fertiliser, on account of nitrate deposition—the net effect of a 50% increase in acid deposition was estimated to be a *benefit* of approximately $50 million. We therefore accept Ashmore's (1991) conclusion that 'in general . . . SO_2 and NO_2, although of importance in local areas with high concentrations, have little economic impact on a national scale, and that the direct effects of acid rain are also likely to be unimportant' (p. 142).[4] We assume that the crop damages from SO_2, NO_2 and acid deposition are 5–10% of the crop damages of ozone air pollution.

Finally, it should be pointed out that the experiments upon which the yield-loss equations are based might not be capturing all of the damages due to ozone air pollution. Ashmore (1991) states that there is 'increasing evidence that pollutants at quite low concentrations can influence pest and pathogen performance . . . [and that] it is apparent that relatively small pollutant-induced changes in pest and pathogen performance could dramatically change the overall economic assessment' (p. 143). Spash (1997) notes that air pollution might also affect the quality as well as the quantity of crops produced; this, of course, might further reduce the value of production. However, we do not attempt to quantify either of these effects.

Dose-response (yield-loss) functions

A dose-response, or yield-loss, function estimates the change in crop yield that results from a change in ozone concentrations. We reviewed the available literature on dose-response functions and selected upper- and lower-bound functions relating levels of ozone to yields of eight major agricultural crops. In the AOM8, we use these functions to estimate yield losses at the county level in the US in 1990. The county-level yield losses then are aggregated to the regional level for the purpose of adjusting the regional production functions in the AOM8. In the simple yield-loss estimates of damages for the crops *not* included in the AOM8, we apply the yield-loss functions to total national value of production for each crop.

The data necessary to estimate these dose-response functions can come from tests in open fields, open-top chambers, or econometric methods. Most of the data in the studies we use come from tests in open-top chambers, in which ozone precursors are injected into the chamber through an inlet to duplicate various ozone exposures. This method, which has been widely employed to assess crop yield responses to ozone (Heck *et al.*, 1984; Rowe and Chestnut, 1985; Heagle *et al.*, 1986; McCool *et al.*, 1986; Olszyk *et al.*, 1988a), has two major advantages over the other alternatives. First, a wide range of ozone concentrations can be applied to examine crop yield-responses. Second, the inside of the open-top chamber is similar to ambient conditions. Hence, the difference between the data generated using this system

[4] We have not seen any evidence that yet other pollutants might be seriously damaging. Mutters *et al.* (1993) report that while formaldehyde, a minor urban air pollutant, does affect bean plants, it is unlikely that even five times the present ambient concentrations would harm plant growth, at least in the short term.

and the data under ambient conditions is very small (Heck *et al.*, 1988).

Typically, the experimental test data are fit to a Weibull function, $Q=\mu\cdot e^{-(OZONE/\gamma)\lambda}$, where Q is the observed yield, *OZONE* is the ozone concentration in parts-per-million (air quality data and estimates are discussed in the next subsection), μ is the hypothetical maximum yield at zero ozone, γ is the ozone concentration when Q is $0{\cdot}37\mu$, and λ is a dimensionless shape parameter. This form is used frequently because it is biologically realistic, it generates an estimated yield that approaches zero as ozone concentrations increase to infinity, and because it is flexible: it becomes an exponential decay function when λ equals one and it approaches a linear function when λ is close to 1·3 (Heck *et al.*, 1988). In this study, we use published dose-response functions to assess the yield losses to crops from ozone in the United States; most of these functions assume this form. For some crops, we were able to locate more than one yield function: for example, we found three for alfalfa, four for corn, five for cotton and two for sorghum. For these crops, we selected the low- and the high-estimating yield functions, thereby establishing low and high scenarios. For the eight major crops included in the AOM8, we use the dose-response functions to estimate the percentage yield change in each county *c* due to a reduction in ozone (*QGAIN*%) using Equation (1). These percentage yield changes are then used to shift the production functions in the AOM8. For the remaining crops *not* included in the AOM8, we apply the yield-loss functions to total national value of production for each crop, as shown in Equation (2).

Air quality modeling and data

The dose-response functions estimate changes in crop yields as a function of changes in ambient ozone levels:

$$\Delta E=f(\Delta P,O)=f(PI,PP,O) \tag{3}$$

where ΔE is the change in the effect of interest (in this analysis, crop yield); ΔP is the change in ambient air pollution; O represents other variables; PI denotes the initial pollution level; and PP denotes the pollution level after the change in pollution, i.e. the level after removing all anthropogenic ozone-precursor emissions (Case I), or 10% or 100% of motor-vehicle related ozone-precursor emissions (Case IIA and IIB, respectively).

The initial pollution level, *PI*, is specified to be the actual ambient air quality in each county or crop growing region of the US. These data are discussed below. We estimate *PP*, in each county, on the assumption that the ratio of *PP* to *PI* is equal to the ratio of the *modeled PP* to *modeled PI*:

$$\frac{PP}{PI}=\frac{PP^*}{PI^*}\rightarrow PP=PI\cdot\frac{PP^*}{PI^*} \tag{4}$$

where PP is the estimated actual ozone level after the change in ozone for each of the three ozone-reduction scenarios; PI is the actual ambient ozone level in 1990 (data from air quality monitors, discussed below); and PP^*/PI^* is the estimated ratio of ozone levels after the change in emissions to ozone levels given the baseline emissions (see Delucchi and McCubbin, 1996 for details). Each of the three ozone-reduction scenarios results in three different values of *PP*. In Delucchi and McCubbin (1996), we develop our estimate of PP^*/PI^*. Here, we summarise the main simplifying assumptions in our model. We do not estimate the absolute air quality given the baseline emissions or the change in emissions, but rather estimate directly the percentage change in air quality itself. That is, in Equation (4), we estimate the *ratio* PP^*/PI^*; we do not estimate PI^* and PP^* individually. To estimate this ratio, we need to know only the relative contribution to ambient ozone of the different emission sources. The ratio PP^*/PI^* can be estimated by assuming that it is equal to the ratio PP'^*/PI'^*, where PP'^* and PI'^* are the emitted pollutants associated with the ambient pollutants PP^* and PI^*. This ratio is estimated based on a model of precursor dispersion and ozone formation (Delucchi and McCubbin, 1996). In essence, our model apportions the known ozone concentration (*PI*) back to individual emissions sources on the basis of dispersion-adjusted emissions of NO_x and VOCs from those sources, where the dispersion adjustments account for differences in location (sources further away from the point of ozone measurement contribute less), emissions height, and other factors, and the VOCs are weighted by their reactivity, or ozone-formation potential. To model the link between emissions and ambient air pollution, we make some simplifications, specifically:

(1). It is assumed that in each county *c*, the ambient pollution measured at the air quality monitors is a function of emissions from all the counties in the same Air Quality Control Region (AQCR) as county *c*.[5] We distinguish between emissions generated within county *c*, and emissions generated in other counties within the same AQCR as county *c*. We do not account for the transport of pollution from one AQCR to another; i.e. it is assumed that air quality in a particular ACQR is a function only of emissions within the AQCR.

(2). It is assumed that emissions of precursor pollutants VOCs and NO_x disperse as such from the source to the receptor (the ambient air quality monitor), and then at the receptor participate in the chemical reactions that produce ozone (O_3). We do not account for meteorology and topography, and assume that the ambient ozone is a function only of the amount precursor emissions at the site of the monitor. (These assumptions are made because we cannot easily model chemical transformations as a function of the distance from the source.) We assume that ozone formation is a non-linear function of the amount of dispersion-adjusted, 'reactivity'-weighted VOC (DRVOC) and dispersion-adjusted NO_x (DNO_x):

$$PP = f(DRVOC^{A}, DNOx^{B}) \tag{5}$$

In this function, the exponent A determines the sensitivity of ozone to changes in VOC levels, and the exponent B determines the sensitivity of ozone to changes in NO_x levels. We picked values for A (0·55) and B (0·40) so that the resulting ozone sensitivities (defined formally as the percentage change in ozone divided by the percentage change in VOC or NO_x) were reasonably consistent with the ozone sensitivities we derived from the results of sophisticated ozone air quality models (Delucchi and McCubbin, 1996). Thus, combining Equations (4) and (5), we estimate the change in ozone due to a change in motor-vehicle emissions as follows:

$$PP = PI \cdot \frac{(DRVOC_{\Delta E})^{0\cdot55} \cdot (DNOx_{\Delta E})^{0\cdot40}}{(DRVOC_{total})^{0\cdot55} \cdot (DNOx_{total})^{0\cdot40}} \tag{6}$$

where $DRVOC_{\Delta E}$ is the dispersion-adjusted, reactivity-weighted emissions of VOCs after the change in emissions ΔE (Cases I, IIA and IIB); $DNOx_{\Delta E}$ is the dispersion-adjusted emissions of NO_x after the change in emissions ΔE; $DRVOC_{total}$ is the total dispersion-adjusted, reactivity-weighted emissions of VOCs from all sources, before the change in emissions ΔE; and $DNOx_{total}$ is the total dispersion-adjusted emissions of NO_x from all sources, before the change in emissions ΔE. The reactivity weights account for the difference in the ozone forming potential of different classes of VOC compounds, and are based on the work of Derwent *et al.* (1996). See Delucchi and McCubbin (1996) for details.

This model of ozone air quality obviously is rather simple. Most problematic, perhaps, is our use of a simple Gaussian dispersion model, without any meteorological or chemical detail, to weight the contribution of each emissions source to the air quality measured at the relevant monitors. Moreover, because we estimate the *ratio PP*/PP**, and not *PI** and *PP** individually in units of concentration, and because of the non-linear relationship between emissions of ozone precursors and ambient ozone levels, there is no sure way for us to validate our estimates. Our results, then, must be viewed with these qualifications in mind.

(3). We attribute to motor-vehicle use, emissions from the production and maintenance of motor fuels, motor vehicles and the motor-vehicle infrastructure. First, we identified all sectors in the USEPA's complete emission inventory that involve activities related to the use of motor vehicles (USEPA, 1992). These sectors include oil and gas extraction, petroleum refining, motor-vehicle manufacture, motor-vehicle service, steel production, road construction, etc. Then, in each of these sectors, we estimated the fraction of the total output or activity that is related to the use of motor vehicles. Finally, with these fractions, we estimated the motor-vehicle related fraction of emissions of each pollutant in each sector. We refer to these as indirect emissions. Details are given in Delucchi (1996). In the summary tables, results are reported with and without these indirect emissions.

To specify the initial (1990) ozone levels in the AOM8, data are used from USEPA air

[5] Air quality control regions are defined in the Code of Federal Regulations (section 40: Part 81).

quality monitors (USEPA, 1992). The USEPA maintains hundreds of air quality monitors throughout the United States, classified according to general location (urban and city center, suburban and rural), and land use (residential, commercial, industrial, agricultural, forest, desert, mobile, blighted area). Wherever possible, data are used from the agricultural monitors. However, many agricultural areas do not have these monitors; in the lower 48 states (we exclude Alaska and Hawaii from our analysis), only 115 of the more than 3000 counties have agricultural monitors. All of the 12 production regions considered do have agricultural monitors. In any agricultural county that lacks ozone data from an agricultural monitor, it is assumed that the ozone level is equal to the mean of the growing-season ozone levels measured at all agricultural monitors in the state. If there are no agricultural monitors in the entire state (there are 10 such states), then we assume that the ozone level in the county is equal to the average of the growing-season levels in the entire region.

In the yield-loss model for the crops *not* included in the AOM8 [Equation (2)], the dose-response function Q is applied to national—not county-level—production of each crop. Hence, the air quality parameter in the Weibull dose-response functions should be the national-average or production-weighted ozone air quality for each crop. Lefohn and Altshuller (1996) report an earlier study of the kriged maximum 7-h and 12-h average ozone concentrations in rural areas of each state in the US in 1985 and 1986. A Kriged ozone value for a particular area (state, in this case) is one that has been estimated by interpolating between readings of available air quality monitors. (This interpolation is necessary because there are relatively few agricultural or rural monitors.) 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 and Altshuller, 1996, pp. 4–43). Given these estimates of average rural ozone air quality in each state, and data on the major producing states for each crop, we can approximate the production-weighted ozone-air quality for all of the crops in the analysis. Our estimate is approximate because we did not actually calculate $\sum_S P_S \cdot OZONE_S / \sum_S P_S$, where P_S is the production in state S, and $OZONE_S$ is the air quality in state S, for each crop; instead, we looked at the air quality and crop production in the major producing states and made a judgment as to the national-average production-weighted air quality. The results are shown in Table 2.

Results of the analysis

Ozone damages to the eight major crops

Tables 3 and 4 show the welfare changes estimated by the AOM8 for the three emission-reduction scenarios, for the eight major crops. (These results in these tables do *not* include effects on crops other than the eight included in the AOM8, or the effects of pollutants other than ozone.) In all cases, the biggest change in producer surplus occurs in the Pacific-II region (California). However, nearly all of the producer surplus change in this region is due to a change in deficiency payments, which, as discussed earlier, are transfers and are not counted in the final welfare tally. The biggest change in producer surplus net of deficiency payments occurs in the Corn Belt. This is because ozone causes substantial losses to soybeans and corn, which are grown mainly in the Corn Belt. Damage to soybeans is large because soybean yield is very sensitive to ozone levels, and the total value of soybean output is high. Corn is only moderately sensitive to ozone, but is by far the most valuable of the eight crops in the aggregate alfalfa hay and especially cotton are sensitive to ozone levels, but only moderately valuable in the aggregate. Barley, rice and sorghum are of minor value; wheat is of moderate value, and is only moderately sensitive to ozone.

Table 4 shows that in 1990, anthropogenic ozone caused between \$2·8 and \$5·8 billion in damages to the eight crops (Case I), and that ozone formed from motor-vehicle emissions caused between \$2·0 and \$3·3billion in damages to these eight crops (Case IIB). Motor-vehicles are responsible for such a large fraction of total damages because most of the ozone precursor pollutants in agricultural areas come from motor vehicles.

Table 3(a). 1990 change in producer surplus and deficiency payments due to ozone air pollution in the markets for eight major crops, Case I (billions of 1990 dollars)

	Change in producer surplus		Change in deficiency payments	
Region	Low	High	Low	High
North-east	0·127	0·276	−0·002	0·023
Lake States	0·207	0·502	−0·014	0·091
Corn Belt	0·755	1·731	−0·072	0·466
Appalachian	0·191	0·367	−0·001	0·038
South-east	0·097	0·190	0·009	0·042
Delta States	0·371	0·995	0·198	0·624
Southern Plains	0·506	1·404	0·368	1·021
Northern Plains	0·114	0·282	0·025	0·113
Mountain-I	0·056	0·101	0·017	0·017
Mountain-II	0·055	0·155	0·013	0·039
Pacific-I	0·010	0·023	0·002	0·002
Pacific-II	2·217	6·045	1·951	5·366
Total	4·707	12·071	2·492	7·844

Case I is a 100% reduction in anthropogenic emissions of VOCs and NO_x.
These are the AOM8 estimates of the effect of ozone air pollution on the eight major crops shown in Table 1. The results shown in this table *do not include* effects on crops other than the eight, or the effects of pollutants other than ozone.

Table 3(b). 1990 change in producer surplus and deficiency payments due to ozone air pollution in the markets for eight major crops, Case IIA (billions of 1990 dollars)

	Direct Emissions Only[a]				Direct + Indirect Emissions[a]			
	Change in producer surplus		Change in deficiency payments		Change in producer surplus		Change in deficiency payments	
Region	Low	High	Low	High	Low	High	Low	High
North-east	0·009	0·015	0·000	0·001	0·009	0·016	0·000	0·001
Lake States	0·015	0·028	−0·001	0·005	0·016	0·030	−0·001	0·005
Corn Belt	0·049	0·094	−0·003	0·026	0·056	0·102	−0·003	0·029
Appalachian	0·011	0·017	0·000	0·002	0·011	0·017	0·000	0·002
South-east	0·005	0·009	0·001	0·002	0·005	0·009	0·001	0·002
Delta States	0·022	0·049	0·013	0·031	0·023	0·051	0·013	0·032
Southern Plains	0·038	0·074	0·027	0·053	0·047	0·085	0·034	0·060
Northern Plains	0·008	0·013	0·002	0·005	0·010	0·015	0·002	0·006
Mountain-I	0·003	0·004	0·001	0·001	0·003	0·005	0·001	0·001
Mountain-I	0·004	0·009	0·001	0·002	0·004	0·010	0·001	0·002
Pacific-I	0·000	0·001	0·000	0·000	0·000	0·001	0·000	0·000
Pacific-II	0·109	0·266	0·096	0·236	0·129	0·275	0·114	0·245
Total	0·271	0·580	0·139	0·368	0·314	0·616	0·164	0·388

Case IIA is a 10% reduction in motor-vehicle related emissions of VOCs and NO_x.
These are the estimates of the effect of ozone air pollution on the eight major crops included in the AOM8. The results shown in this table *do not include* effects on crops other than the eight, or the effects of pollutants other than ozone.
[a] Direct emissions are tailpipe and evaporative emissions from motor vehicles. Indirect emissions include emissions from the production of motor fuels, the servicing of motor vehicles, the production of crude oil used to make motor fuel, the production of motor vehicles, etc. See Delucchi (1996) for details.

Table 3(c). 1990 change in producer surplus and deficiency payments due to ozone air pollution in the markets for eight major crops, Case IIB (billions of 1990 dollars)

	Direct Emissions Only[a]				Direct + Indirect Emissions[a]			
	Change in producer surplus		Change in deficiency payments		Change in producer surplus		Change in deficiency payments	
Region	Low	High	Low	High	Low	High	Low	High
North-east	0·089	0·189	−0·001	0·015	0·094	0·193	−0·001	0·016
Lake States	0·163	0·318	−0·010	0·059	0·175	0·332	−0·011	0·061
Corn Belt	0·497	0·985	−0·042	0·266	0·566	1·077	−0·050	0·290
Appalachian	0·118	0·208	0·001	0·022	0·121	0·212	0·001	0·022
South-east	0·055	0·107	0·006	0·024	0·055	0·107	0·008	0·024
Delta States	0·224	0·541	0·124	0·341	0·232	0·552	0·130	0·349
Southern Plains	0·349	0·706	0·252	0·513	0·421	0·798	0·304	0·577
Northern Plains	0·081	0·127	0·018	0·054	0·099	0·147	0·020	0·060
Mountain-I	0·037	0·054	0·013	0·011	0·040	0·055	0·014	0·012
Mountain-II	0·037	0·095	0·009	0·025	0·040	0·098	0·010	0·026
Pacific-I	0·006	0·013	0·002	0·001	0·006	0·013	0·002	0·001
Pacific-II	1·081	2·915	0·955	2·586	1·253	3·003	1·108	2·666
Total	2·738	6·257	1·329	3·916	3·100	6·588	1·534	4·105

Case IIB is a 100% reduction in motor-vehicle related emissions of VOCs and NO_x.
These are the estimates of the effect of ozone air pollution on the eight major crops included in the AOM8. The results shown in this table *do not include* effects on crops other than the eight, or the effects of pollutants other than ozone.
[a] Direct emissions are tailpipe and evaporative emissions from motor vehicles. Indirect emissions include emissions from the production of motor fuels, the servicing of motor vehicles, the production of crude oil used to make motor fuel, the production of motor vehicles, etc. See Delucchi (1996) for details.

Table 4. 1990 total change in welfare in the markets for eight major crops due to a reduction in ozone air pollution (billions of 1990 dollars)

	Case I		Case IIA				Case IIB			
			Direct emissions[a]		Direct + indirect[a]		Direct emissions[a]		Direct + indirect[a]	
	Low	High	Low	High	Low	High	Low	High	Low	High
Change in producer surplus[b]	4·71	12·07	0·27	0·58	0·31	0·61	2·74	6·25	3·10	6·59
Change in deficiency payments[b]	2·49	7·85	0·14	0·37	0·16	0·39	1·33	3·91	1·53	4·11
Change in consumer surplus	0·63	1·53	0·03	0·08	0·04	0·08	0·39	0·80	0·44	0·86
Change in total welfare[c]	2·84	5·76	0·17	0·28	0·19	0·30	1·80	3·14	2·01	3·34

Case I is a 100% reduction in anthropogenic emissions of VOCs and NO_x. Cases IIA and IIB are a 10% and a 100% reduction in motor-vehicle related emissions of VOCs and NO_x, respectively.
These are the estimates of the effect of ozone air pollution on the eight major crops included in the AOM8. The results shown in this table *do not include* effects on crops other than the eight, or the effects of pollutants other than ozone.
[a] Direct emissions are tailpipe and evaporative emissions from motor vehicles. Indirect emissions include emissions from the production of motor fuels, the servicing of motor vehicles, the production of crude oil used to make motor fuel, the production of motor vehicles, etc. See Delucchi (1996) for details.
[b] From Tables 3a–3c.
[c] Equals the change in producer surplus minus the change in deficiency payments plus the change in consumer surplus.

Some annual variation in these estimates due to fluctuations in meteorological conditions is to be expected, although during the past decade, these fluctuations have been rather modest. From 1987 to 1996, the second daily maximum 1-h ozone concentration for 194 rural monitoring sites ranged between about 0·11 and 0·12 ppm (USEPA, 1998). Note that

Table 5. 1990 change in welfare in all markets due to a reduction in motor-vehicle related emissions (billions of 1990 dollars)

	Direct emissions[a]		Direct + indirect[a]	
Case IIA: 10% reduction in emissions	Low	High	Low	High
Light-duty gasoline automobiles (LDGA)	0·16	0·30	0·19	0·32
Light-duty gasoline trucks (LDGT)	0·07	0·13	0·07	0·14
Heavy-duty gasoline vehicles (HDGV)	0·01	0·02	0·01	0·02
Case IIA, All gasoline vehicles	*0·25*	*0·44*	*0·28*	*0·47*
Light-duty diesel automobiles (LDDA)	0·00	0·00	0·00	0·02
Light-duty diesel trucks (LDDT)	0·00	0·00	0·00	0·00
Heavy-duty diesel vehicles (HDDV)	0·04	0·09	0·05	0·09
Case IIA, All diesel vehicles	*0·05*	*0·09*	*0·05*	*0·09*
Case IIA, All gasoline and diesel vehicles	0·30	0·52	0·33	0·57
Case IIB: 100% reduction in emissions	3·15	5·76	3·50	6·14

These results *do include* effects on crops other than those included in the AOM8, and the effects of pollutants other than ozone.

[a] Direct emissions are tailpipe and evaporative emissions from motor vehicles. Indirect emissions include emissions from the production of motor fuels, the servicing of motor vehicles, the production of crude oil used to make motor fuel, the production of motor vehicles, etc. See Delucchi (1996) for details.

in Table 4, the damages for Case IIB, a 100% reduction in motor-vehicle ozone-precursor emissions, are not exactly 10 times the damages in Case IIA, which is a 10% reduction in motor-vehicle ozone-precursor emissions. This is because the ozone-production function and the agricultural production model are non-linear. However, the Case IIB results are *close* to 10 times the Case IIA results, which implies that, for our model anyway, the total-cost function actually is fairly linear with emissions and hence vehicle-miles of travel, and that in this case, average cost is a reasonably proxy for any marginal cost.

Damages attributable to motor-vehicle classes, including damages from pollutants other than ozone, and damages to other crops

Tables 5 and 6 show agricultural damages attributable to six different classes of motor vehicles, including indirect emissions as well as direct emissions from vehicles themselves. The costs were allocated based on emissions of NO_x and VOC emissions from each vehicle class. We used the USEPA emission inventory (USEPA, 1992), but adjusted the VOC and NO_x emissions from LDVs upwards, because it is widely believed that the USEPA emissions model, MOBILE5, underestimates these emissions (Delucchi and McCubbin, 1996).

The damage estimates in these tables, unlike the estimates in Tables 5 and 6, include ozone damages to crops other than the eight in the AOM8, and damages from pollutants other than ozone. We estimate that gasoline vehicles cause much greater damages than do diesel vehicles, because they emit more VOCs, which is one of the two main precursors to ozone formation. In all cases, the inclusion of indirect emissions—from petroleum refineries making transportation fuels, oil-production fields, motor-vehicle factories and so on—increases damages by only 10%.

Table 6 shows costs per kilogram of NO_x and VOC combined because these pollutants are emitted simultaneously and contribute jointly to ozone production. We did not estimate the effect of removing *only* NO_x or *only* VOCs because it is unlikely that any policy will remove one but not the other. Thus, we cannot report dollar-per-kilogram results for each pollutant individually. Moreover, technically, the costs-per-kilogram-of-NO_x-and-VOC-combined results of Table 4 hold only for the actual proportions of VOCs and NO_x

Table 6. 1990 change in welfare in all markets due to a 10% reduction in motor-vehicle related emissions (1990 $/1000-VMT, and 1990 $/kg-[VOCs + NO_x])

	$/1000-VMT[a]				$/kg-[VOCs + NO_x][b]			
	Direct emissions[c]		Direct + Indirect[c]		Direct emissions[c]		Direct + Indirect[c]	
Case IIA: 10% reduction in emissions	Low	High	Low	High	Low	High	Low	High
Light-duty gasoline automobiles (LDGA)	1·06	1·89	1·21	2·04	0·20	0·31	0·18	0·28
Light-duty gasoline trucks (LDGT)	1·78	3·17	2·04	3·43	0·21	0·33	0·19	0·29
Heavy-duty gasoline vehicles (HDGV)	4·26	7·01	4·88	7·67	0·15	0·25	0·14	0·22
Case IIA, All gasoline vehicles	*1·24*	*2·22*	*1·42*	*2·39*	*0·20*	*0·31*	*0·18*	*0·28*
Light-duty diesel automobiles (LDDA)	0·40	0·61	0·43	7·95	0·22	0·35	0·20	3·71
Light-duty diesel trucks (LDDT)	0·14	0·24	0·21	0·30	0·22	0·35	0·15	0·21
Heavy-duty diesel vehicles (HDDV)	3·63	6·13	3·94	6·43	0·20	0·34	0·18	0·30
Case IIA, All diesel vehicles	*2·87*	*4·84*	*3·13*	*5·09*	*0·20*	*0·34*	*0·18*	*0·30*
Case IIA, All gasoline and diesel vehicles	1·38	2·44	1·56	2·62	0·20	0·32	0·18	0·28
Case IIB: 100% reduction in emissions	1·46	2·68	1·63	2·86	0·21	0·35	0·19	0·31

These results *do include* effects on crops other than those included in the AOM8, and the effects of pollutants other than ozone.
[a] VMT = vehicle-miles of travel. These values are calculated by dividing the dollar results of Table 5 by thousands of miles traveled in each vehicle class.
[b] These values are calculated by dividing the dollar results of Table 5 by the sum of VOC and NO_x from each vehicle class and associated indirect emission sources.
[c] Direct emissions are tailpipe and evaporative emissions from motor vehicles. Indirect emissions include emissions from the production of motor fuels, the servicing of motor vehicles, the production of crude oil used to make motor fuel, the production of motor vehicles, etc. See Delucchi (1996) for details.

emitted in 1990. However, the results probably are reasonably accurate for up to moderate deviations from the 1990 proportions. The dollars-per-kilogram results are more useful than the dollars-per-vehicle-mile-traveled results because they are independent of the kilogram-per-mile emission rate of motor vehicles, and hence can be applied to any assumed or estimated emission rate from any kind of vehicle using any kind of fuel.

A final caution: we have *assumed* that the aggregate scaling factor that accounts for damages due to pollutants other than ozone applies to each specific vehicle class, but this might not actually be correct. If, for example, the non-ozone damages are due mainly to SO_2 emissions, then diesel-fuel vehicles, which emit relatively high amounts of SO_2, are responsible for a larger share of total (ozone + SO_2) damages than they are of ozone damages alone. We did not estimate 'other pollutant' scaling factors specific to each vehicle class because we did not determine which ambient pollutants (and hence which emissions) are responsible for the non-ozone damages.

Comparison of our results with those of other studies

Our results in Table 4 are consistent with other published estimates. We estimate that a 100% reduction in anthropogenic ozone would create benefits of $2·8–5·8 billion in 1990 for the eight major crops included in the AOM8. This range is broadly consistent with the range estimated by Adams *et al.* (1989), Krupnick and Kopp (1988), and Adams *et al.* (1986) for reductions in total ambient ozone levels of 25–50%. By 'broadly consistent,' we mean that our estimated benefits for a 100% reduction in anthropogenic ozone are of the same order of magnitude as twice the benefits of a 50% reduction or four times the benefits of a 25% reduction in total ozone estimated in the other studies. Put another way, we expect that if the models in the other studies had estimated benefits for a 100% reduction in anthropogenic ozone, they would have produced results of the same order of magnitude as ours. (Note that in this comparison, we do not include our estimates of benefits to crops other than eight modeled here, or of benefits from reducing pollutants other than ozone.)

Conclusion

An agricultural production model (AOM8) has been used to estimate the change in consumer surplus and producer surplus resulting from a decrease in ozone from actual 1990 levels to background levels or the levels with 10% or 100% of motor-vehicle related emissions eliminated. The model includes all production regions of the United States, and eight major crops that account for some 63% of the total value of United States agricultural production. We find that motor-vehicle ozone damage to these eight crops amounts to about \$2–3 billion. When ozone damages to other crops, and damages to all crops from all other pollutants are also considered, pollution attributable to motor-vehicle use probably causes \$3–6 billion in agricultural damages annually. These estimated damages are much less than the damages to human health (McCubbin and Delucchi, 1996), and thus probably constitute a relatively minor, but non-trivial, portion of the total cost of air pollution from motor vehicles. Even a modest 10% reduction in motor-vehicle emissions may yield about \$0·5 billion in economic benefits. These results lend some support to the USEPA's decision in 1997 to revise the secondary National Ambient Air Quality Standards for ground-level ozone from a 1-h standard of 0·12 ppm to an 8-h standard of 0·08 ppm. The USEPA believes that attaining this new 8-h standard will substantially protect vegetation and is currently working to enhance rural ozone monitoring (USEPA, 1998).

Acknowledgements

Support for the social-cost analysis was provided by Pew Charitable Trusts, the Federal Highway Administration (through Battelle Columbus Laboratory), the University of California Transportation Center, the University of California Energy Research Group (now the University of California Energy Institute) and the US Congress Office of Technology Assessment. Richard Howitt developed the original agricultural production used in this analysis. Of course, we alone are responsible for the contents of this paper.

References

Adams, R. M. and Crocker, T. D. (1989). The agricultural economics of environmental change: some lessons from air pollution. *Journal of Environmental Management* **28**, 295–307.

Adams, R. M. and McCarl, B. A. (1985). Assessing the benefits of alternative ozone standards on agriculture: the role of response information. *Journal of Environmental Economics and Management* **12**, 264–276.

Adams, R. M., Crocker, T. D. and Thanavibulchai, N. (1982). An economic assessment of air pollution damages to selected annual crops in southern California. *Journal of Environmental Economics and Management* **9**, 42–58.

Adams, R. M., Hamilton, S. A. and McCarl, B. A. (1984). *The Economic Effects of Ozone on Agriculture*. EPA-600/3-84-090. Corvallis, OR: US Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory.

Adams, R. M., Glyer, J. D., Johnson, S. L. and McCarl, B. A. (1989). A reassessment of the economic effects of ozone on US agriculture. *Journal of the Air Pollution Control Association* **39**, 960–968.

Adams, R. M., Hamilton, S. A. and McCarl, B. A. (1986). The benefits of pollution control: the case of ozone and US agriculture. *American Journal of Agricultural Economics* **68**, 886–889.

Ashmore, M. R. (1991). Air pollution and agriculture. *Outlook on Agriculture* **20**, 139–144.

Brown, D. and Smith, M. (1984). Crop substitution in the estimation of economic benefits due to ozone reduction. *Journal of Environmental Economics and Management* **11**, 347–362.

Bureau of the Census (1989). *1987 Census of Agriculture, Geographic Area Series*. AC-87-A-<1 to 50>, 50 parts. Washington, DC: US Department of Commerce.

California Air Resources Board (1987). *Effects of Ozone on Vegetation and Possible Alternative Ambient Air Quality Standards, Staff Report*. Sacramento: California Air Resources Board.

Davis, S. C. (1997). *Transportation Energy Data Book: Edition 17*. ORNL-6919. Oak Ridge, TN: Oak Ridge National Laboratory.

Delucchi, M. A. (1996). *The Allocation of the Social Costs of Motor-vehicle Use to Six Classes of Motor Vehicles*. UCD-ITS-RR-96-3 (10). Davis, CA: Institute of Transportation Studies, University of California at Davis.

Delucchi, M. A. and McCubbin, D. R. (1996). *The Contribution of Motor Vehicles and Other Sources to Ambient Air Pollution*. UCD-ITS-RR-96-3 (16). Davis, CA: Institute of Transportation Studies, University of California at Davis.

Delucchi, M. A., Murphy, J., Kim, J. and McCubbin, D. R. (1996). *The Cost of Crop Damage Caused by Ozone Air Pollution from Motor-Vehicles*. UCD-ITS-RR-96-3 (12). Davis, CA: Institute of Transportation Studies, University of California at Davis.

Derwent, R. G., Jenkin, M. E. and Saunders, S. M. (1996). Photochemical ozone creation potentials for a large number of reactive hydrocarbons under European conditions. *Atmospheric Environment* **30**, 181–199.

Energy and Resource Consultants, Inc. (1985). *Economic Assessment of the Effects of Air Pollution on Agricultural Crops in the San Joaquin Valley*. California Air Resources Board Contract A2-054-32. Boulder, CO: Energy and Resource Consultants, Inc.

Heagle, A. S., Heck, W. W., Lesser, V. M., Rawlings, J. O. and Mowry, F. L. (1986). Injury and yield response of cotton to chronic doses of ozone and sulfur dioxide. *Journal of Environmental Quality* **15**, 375–382.

Heck, W. W. and Brandt, C. S. (1977). Effects of air pollution on vegetation. In *Air Pollution*, Volume 2, (A. C. Stern, ed.) New York: Academic Press.

Heck, W. W., Taylor, O. C., Adams, R., Bingham, G., Miller, J., Preston, E. and Weinstein, L. (1982). Assessment of crop loss from ozone. *Journal of the Air Pollution Control Association* **32**, 353–361.

Heck, W. W., Cure, W. W., Rawlings, J. O., Zaragoza, L. J., Heagle, A. S., Heggestad, H. E., Kohut, R. J., Kress, L. W. and Temple, P. J. (1984). Assessing impacts of ozone on agricultural crops: II. crop yield functions and alternative exposure statistics. *Journal of the Air Pollution Control Association* **34**, 810–817.

Heck, W. W., Taylor, O. C. and Tingey, D. T. (1988). *Assessment of Crop Loss From Air Pollutants*. New York: Elsevier Applied Science.

Herrick, C. N. and Kulp, J. L. (1987). *Interim Assessment: The Causes and Effects of Acidic Deposition*. Volume 1, Executive Summary. Washington, DC: National Acid Precipitation Assessment Program, Office for the Director of Research.

Howitt, R. E. (1991). *Calibrated Models for Agricultural Production and Environmental Analysis*. Working Paper 91-10. Davis, CA: University of California at Davis, Department of Agricultural Economics.

Howitt, R. E. and Goodman, C. (1989). *The Economic Assessment of California Field Crop Losses Due to Air Pollution, Final Report*. Contract #A5-105-32. Sacramento: California Air Resources Board.

Howitt, R. E., Gossard, T. W. and Adams, R. M. (1984). Effects of alternative ozone concentrations and response data on economic assessments: the case of California crops. *Journal of the Air Pollution Control Association* **34**, 1122–1127.

Kopp, R. J., Vaughan, W. J., Hazilla, M. and Carson, R. (1985). Implications of environmental policy for US agriculture: the case of ambient ozone standards. *Journal of Environmental Management* **20**, 321–331.

Krupnick, A. J. and Kopp, R. J. (1988). *The Health and Agricultural Benefits of Reductions in Ambient Ozone in the United States*. Discussion Paper QE88-10. Resources for the Future, Quality of the Environmental Division.

Lefohn, A. S. and Altshuller, A. P. (1996). Environmental concentrations, patterns, and exposure estimates. In *Air Quality Criteria for Ozone and Related Photochemical Oxidants*. Vol. II. Washington, DC: US Environmental Protection Agency, Office of Research and Development.

Lesser, V. M., Rawlings, J. O., Spruill, S. E. and Somerville, M. C. (1990). Ozone effects on agricultural crops: Statistical Methodologies and estimated dose-response relationships. *Crop Science* **30**, 148–155.

McCool, P. M., Musselman, R. C., Tesa, R. R. and Oshima, R. J. (1986). Determining crop yield losses from air pollutants. *California Agriculture* **40**, 9–10.

McCubbin, D. R. and Delucchi, M. A. (1996). *The Social Cost of the Health Effects of Motor-Vehicle Air Pollution*. UCD-ITS-RR-96-3 (11). Davis, CA: University of California at Davis, Institute of Transportation Studies.

Mjelde, J. W., Adams, R. M., Dixon, B. L. and Garcia, P. (1984). Using farmers' actions to measure crop loss due to air pollution. *Journal of the Air Pollution Control Association* **34**, 360–364.

Murphy, J. J. and Delucchi, M. A. (1998). Review of the literature on the social cost of motor vehicle use in the United States. *Journal of Transportation and Statistics* **1**, 15–42.

Mutters, R. G., Madore, M. and Bytnerowicz, A. (1993). Formaldehyde exposure affects growth and metabolism of common bean. *Journal of the Air and Waste Management Association* **43**, 113–116.

National Agricultural Statistics Service (1995a). *Crop Values, Final Estimates for 1987–1992*. Statistical Bulletin No. 903. Washington, DC: US Department of Agriculture.

National Agricultural Statistics Service (1995b). *Vegetable Crops, Final Estimates by States, 1987–1992*. Statistical Bulletin No. 902. Washington, DC: US Department of Agriculture.

National Agricultural Statistics Service (1995c). *Noncitrus Fruits and Nuts, Final Estimates for 1987–1992*. Statistical Bulletin No. 900. Washington, DC: US Department of Agriculture.

National Agricultural Statistics Service (1995d). *Citrus Fruits: Revised Estimates for 1986–87 to 1992–93*. Statistical Bulletin No. 899. Washington, DC: US Department of Agriculture.

Olszyk, D. M., Cabrera, H. and Thompson, C. R. (1988a). California statewide assessment of the effects of ozone on crop productivity. *Journal of* *the Air Pollution Control Association* **38**, 928–931.

Olszyk, D. M., Thompson, C. R. and Poe, M. P. (1988b). Crop loss assessment for California: modeling losses with different ozone standard scenarios. *Environmental Pollution* **53**, 303–311.

Rowe, R. D. and Chestnut, L. G. (1985). Economic assessment of the effects of air pollution on agricultural crops in the San Joaquin Valley. *Journal of the Air Pollution Control Association* **35**, 728–734.

Spash, C. L. (1997). Assessing the economic benefits to agriculture from air pollution control. *Journal of Economic Surveys* **11**, 47–70.

US Department of Agriculture (USDA), (1992). *Agricultural Statistics, 1992*. Washington, DC: US Government Printing Office.

US Environmental Protection Agency (USEPA). (1992). *Aerometric Information Retrieval System (AIRS)*. Research Triangle Park, NC: Office of Air Quality Planning and Standards.

US Environmental Protection Agency, Office of Air Quality Planning and Standards (USEPA). (1996). *Review of National Ambient Air Quality Standards for Ozone: Assessment of Scientific and Technical Information*. Research Triangle Park, NC: US Environmental Protection Agency.

US Environmental Protection Agency, Office of Air Quality Planning and Standards (USEPA). (1998). *National Air Quality and Emission Trends Report, 1996*. EPA 454/R-97-013. Research Triangle Park, NC: US Environmental Protection Agency.