THE COST OF CROP DAMAGE CAUSED BY OZONE AIR POLLUTION FROM MOTOR VEHICLES

Report #12 in the series: *The Annualized Social Cost of Motor-Vehicle Use in the United States, based on 1990-1991 Data*

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LIST OF ACRONYMS AND ABBREVIATIONS AND OTHER NAMES

The following are used throughout all the reports of the series, although not necessarily in this particular report

AER = *Annual Energy Review* (Energy Information Administration)
AHS = *American Housing Survey* (Bureau of the Census and others)
ARB = Air Resources Board
BLS = Bureau of Labor Statistics (U. S. Department of Labor)
BEA = Bureau of Economic Analysis (U. S. Department of Commerce)
BTS = Bureau of Transportation Statistics (U. S. Department of Transportation)
CARB = California Air Resources Board
CMB = chemical mass-balance [model]
CO = carbon monoxide
dB = decibel
DOE = Department of Energy
DOT = Department of Transportation
EIA = Energy Information Administration (U. S. Department of Energy)
EPA = United States Environmental Protection Agency
EMFAC = California's emission-factor model
FHWA = Federal Highway Administration (U. S. Department of Transportation)
FTA = Federal Transit Administration (U. S. Department of Transportation)
GNP = Gross National Product
GSA = General Services Administration
HC = hydrocarbon
HDDT = heavy-duty diesel truck
HDDV = heavy-duty diesel vehicle
HDGT = heavy-duty gasoline truck
HDGV = heavy-duty gasoline vehicle
HDT = heavy-duty truck
HDV = heavy-duty vehicle
HU = housing unit
IEA = International Energy Agency
IMPC = Institutional and Municipal Parking Congress
LDDT = light-duty diesel truck
LDDV = light-duty diesel vehicle
LDGT = light-duty gasoline truck
LDGV = light-duty gasoline vehicle
LDT = light-duty truck
LDV = light-duty vehicle
MC = marginal cost
MOBILE5 = EPA's mobile-source emission-factor model.
MSC = marginal social cost

MV = motor vehicle
NIPA = National Income Product Accounts
NO_X = nitrogen oxides
NPTS = Nationwide Personal Transportation Survey
OECD = Organization for Economic Cooperation and Development
O_3 = ozone
OTA = Office of Technology Assessment (U. S. Congress; now defunct)
PART5 = EPA's mobile-source particulate emission-factor model
PCE = Personal Consumption Expenditures (in the National Income Product Accounts)
PM = particulate matter
PM_{10} = particulate matter of 10 micrometers or less aerodynamic diameter
$PM_{2.5}$ = particulate matter of 2.5 micrometers or less aerodynamic diameter
PMT = person-miles of travel
RECS = Residential Energy Consumption Survey
SIC = standard industrial classification
SO_X = sulfur oxides
TIA = *Transportation in America*
TSP = total suspended particulate matter
TIUS = *Truck Inventory and Use Survey* (U. S. Bureau of the Census)
USDOE = U. S. Department of Energy
USDOL = U. S. Department of Labor
USDOT = U. S. Department of Transportation
VMT = vehicle-miles of travel
VOC = volatile organic compound
WTP = willingness-to-pay

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12. THE COST OF CROP DAMAGE CAUSED BY OZONE AIR POLLUTION FROM MOTOR VEHICLES

12.1 INTRODUCTION

The detrimental effects of ambient ozone on crops, even at relatively low concentrations, are well-established (Thompson et al., 1976; Heck and Brandt, 1977; Heck et al., 1982; Environmental Protection Agency, 1984; California Air Resources Board, 1987; Olszyk et al., 1988a, 1988b; Heagle et al., 1986; McCool et al., 1986, Ashmore, 1991). Ozone enters plant leaves through the stomatal openings in the leaf surface and then produces byproducts that reduce the efficiency of photosynthesis (CARB, 1987). Research summarized later in this report suggests that ozone, either alone or in combination with nitrogen dioxide and sulfur dioxide, is responsible for virtually all U.S. crop losses resulting from air pollution. 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. In this paper we use a formal optimization model of agricultural production and demand to estimate damage[1] to eight major crops by all anthropogenic ozone air pollution, and by ozone air pollution attributable to motor-vehicle use. We use yield-loss (dose-response) functions, without a formal model of agricultural production and demand, to account for ozone damages to crops other than the eight in the formal model, and then apply a simple scaling factor to account for the minor damages by pollutants other than ozone. Our analysis is limited to the U. S. and the year 1990.

12.2 THEORETICAL DISCUSSION

12.2.1 Changes in producer and consumer surplus due to a reduction in ambient ozone concentrations

Figure 12-1 demonstrates the theoretical effects on crop output of an improvement in air quality. When the air is polluted, fewer crops are produced from a given set of production inputs than when the air is clean. Thus, by reducing air pollution from existing levels (superscript *o*) to background (superscript *b*), the supply

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[1] 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 -- the benefit that would be realized if the emissions were eliminated. In this sense, "cost of pollution," "pollution damage" and "benefit of reducing pollution" all refer to the same thing in this report.

curve shifts down[2] and probably becomes more elastic (i.e., more price responsive), from S^o to S^b. This reduces the price from P^o to P^b and increases the equilibrium quantity from Q^o to Q^b.

Society gains in economic welfare as a result of this shift in the supply curve[3]. Consumer welfare, as measured by consumer surplus, is improved in two ways. First, the original quantity of crops Q^o is still consumed, but at the lower price P^b (areas 1 and 2 of Figure 12-1). Second, the total quantity of crops consumed is increased, resulting in a gain of new consumer surplus from the additional consumption (area 3). Producers also gain in two ways. First, improved air quality results in a lower cost of production, and saves real resource costs for the original quantity of crops (areas 2 and 4). Second, the increased production results in a gain of producer surplus from the additional revenues from the additional crops (area 5). However, producers also realize a loss in welfare due to the lower crop prices: some of the original producer surplus becomes consumer surplus as a result of the lower price (area 1).

In summary, areas 2, 3, 4, and 5 of Figure 12-1 represent the net benefit to society resulting from the shift in the supply curve. Areas 1, 2 and 3 are the net benefit to consumers; areas 4 and 5, less area 1, are the net benefit to producers.

12.2.2 The effects of a crop price subsidy on social welfare

The analysis of the welfare effects of pollution is complicated a bit if there are subsidies to producers. In 1990, which is the year of our analysis, the Federal government did indeed provide subsidies, called "deficiency payments." A deficiency payment was the difference between the market price and some higher, guaranteed price, multiplied by the quantity affected. Because these deficiency payments were a substantial fraction of the total market value of crops, they significantly affected market

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[2] Let us consider this formally. The yield-loss functions that we use estimate the yield at one ozone level relative to the yield at another ozone level. Hence, we estimate a percentage change in yield for any change in ozone, independent of the quantity of production (see eq. 12-12). This means that if D^o worth of inputs produce Q^o units of crop at ozone level *o*, then at ozone level *b* the D^o units of input would produce $Q^o \cdot (1+QGAIN\%/100)$ units, where QGAIN% is the percentage change in yield at ozone level *b* versus level *o* (see eq. 12-6b). Thus, at ozone level *o*, the average cost is D^o/Q^o; and at ozone level *b*, it is $D^o/(Q^o \cdot (1+QGAIN\%/100))$. If ozone level *b* is less than ozone level *o*, then:

$QGAIN\% > 0$ (because yield increases as ozone declines);
$Q^o \cdot (1+QGAIN\%/100) > Q^o$; and
$D^o/Q^o > D^o/(Q^o \cdot (1+QGAIN\%/100))$.

Now, the average cost of producing any quantity Q is the area under the supply curve up to quantity Q, divided by Q. Thus, if the average cost at any quantity Q is less at ozone level *b* than at ozone level *o*, the supply curve at ozone level *b* must lie below the supply curve at ozone level *o*.

[3] Economic welfare is defined as the sum of producer and consumer surpluses.

prices and quantities, and hence total producer and consumer surplus. Consequently, it is important to understand, and properly treat, the welfare effects of these price subsidies.[4]

Suppose that the supply and demand situation for a crop is as shown in Figure 12-2. The supply curve, S, is the long-run marginal cost of production. If there is no guaranteed price, the equilibrium market price and quantity will be P* and Q*. Producer surplus is equal to the area So-X-P*, consumer surplus equals the area Do-X-P*, and social welfare is simply the sum of these two areas.

Suppose, though, that the government guarantees the price Pd to the farmers. If Pd exceeds P*, as it does in Figure 12-2, then additional, less productive land will be brought into production, thereby increasing the crop supply from Q* to Q′. At Q′, which is what suppliers are willing to supply at the guaranteed price Pd, consumers will be willing to pay only P′ — which is less than P* — because of diminishing marginal utility for the additional consumption. The government now will have to make up the difference between the Pd that it promises farmers and the P′ that consumers are willing to pay. The result is a deficiency payment equal to the area Pd-A-B-P′.

Consumers and producers of crops benefit from this subsidy, although society as whole does not. Relative to the unsubsidized equilibrium, consumers of crops gain area P*-X-B-P′ because: i) they can still consume the quantity Q*, but at a lower market price (area P*-X-C-P′); and ii) they gain additional consumer surplus resulting from the increased consumption (area X-C-B). Crop producers gain area P*-X-A-Pd because: i) they still sell the quantity Q*, but at a higher price (area P*-X-E-Pd), and ii) they enjoy additional benefits from the increased quantity sold (area X-E-A). However, the cost of these extra benefits is the amount of the subsidy itself, paid by taxpayers. This cost exceeds the benefits, and so in the end, the effect of the subsidy is a diminution in social welfare -- the deadweight loss (area X-A-B). In summary, the changes in welfare due to deficiency payments (compared to no deficiency payments) are:

Taxpayers:	lose Pd-A-B-P′ (which equals the deficiency payment)
Crop consumers:	gain P*-X-B-P′
Crop producers:	gain P*-X-A-Pd
Cost of subsidy to society:	**lose X-A-B**

Thus, although consumers and producers of crops benefit from price subsidies, society as a whole loses, because the cost to taxpayers exceeds the benefits to crop consumer and producers, by the amount of the deadweight loss.

What are the implications of this for our analysis? There are two questions that we must answer. First, should deficiency payments be included in the model of the affect of ozone on crop price and quantity (eq. 12-5 below)? The answer to this is “yes”, because

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[4] Deficiency payments were eliminated by Congress with the recent passage of the 1996 Farm Bill.

deficiency payments did indeed affect prices and quantities in the baseline year of 1990. Thus, we include deficiency payments, equal to the subsidy (deficiency) price multiplied by the quantity, in our maximization problem, which in essence is to find the input levels that maximize social surplus (CS+PS) in all crop markets. Because the deficiency payments are included in the welfare maximization, we find (via a production function, eq. 12-6) the quantity Q′ (not the unsubsidized quantity Q*), which then is substituted into a demand equation (eq. 12-7) to find the equilibrium price P′ (not the unsubsidized price P*).

Second, given an estimate of the change in price and quantity due to a change in ozone, how should deficiency payments be treated in the estimation of the change in net social benefits? The short answer is: the deficiency payments, which for the purpose of calculating price and quantity changes (in the maximization problem, below) are included as a gain to producers and consumers, must be excluded from the estimated net benefits to society as a whole.

We define producer surplus with respect to the guaranteed or subsidized price Pd --area So-A-Pd of Figure 12-2. (However, as shown by eq. 12-2, we actually calculate producer surplus as: market price times quantity [area P′-B-Q′-0 of Figure 12-2] plus deficiency payments [area Pd-A-B-P′] less all producer costs [area So-A-Q′-0].) We define consumer surplus with respect to the market price P′ -- area Do-B-P′ of Figure 12-2 below (see eq. 12-3). However, because the deficiency payments are a transfer, and not a net benefit, we cannot simply add the producer and consumer surplus thus calculated to produce an estimate of net social benefits -- which we could do in the absence of a subsidy. Rather, we must deduct the entire amount of the deficiency payment from the estimated social surplus. Therefore, we define net social benefits, or social welfare, as producer surplus plus consumer surplus *less all deficiency payments (area Pd-A-B-P')*. The deduction of deficiency payments accounts for the welfare transfer and deadweight loss[5].

12.3 LITERATURE REVIEW

12.3.1 Introduction

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[5] We thus end up first adding deficiency payments in our measure of producer surplus, and then subtracting them in our measure of net social benefits (net of transfers and deadweight loss). Of course, we could have avoided this simply by defining producer surplus with respect to the market price P′ rather than with respect to the subsidized price Pd. However, it seems more natural to define producer surplus with respect to the price that producers actually receive, and to produce a separate measure of deficiency payments that has to be subtracted from the reported PS and CS in order to get true net social benefits.

Over the last 15 years, there have been many studies that attempt to estimate the economic effects of reduced agricultural production due to ozone. Most of these have analyzed regional impacts (e.g., Adams, Crocker, Thanavibulchai, 1982; Howitt et al., 1984; Energy Resources Consultants, 1985; Adams and McCarl, 1985; Mjelde et al., 1985; Rowe and Chestnut, 1985; Howitt et al., 1989); only a few have analyzed national impacts (e.g., Kopp et al., 1985; Adams et al., 1986; Adams et al., 1989). (See also Spash, 1997, for a good recent review).

Most of these analyses use a mathematical programming model to estimate crop losses due to ozone pollution. These programming models use dose-response functions, estimated on the basis of experimental data, to estimate the change in agricultural output due to a change in pollution. A few studies (e.g., Mjelde et al., 1984; Garcia et al., 1986) use an econometric approach to estimate the impact of pollution on crops. In this approach, actual farm output is estimated as a function of actual pollution levels and other variables.

Econometric models have some advantages over mathematical programming models, but demand data that generally are hard to get. Econometric models are based on actual field data, whereas mathematical programming models usually are based on experimental data for crop yield responses to ozone. Also, the reliability of the econometric model can be statistically tested (Mjelde et al., 1984; Garcia et al., 1986), whereas the mathematical programming model can not provide information necessary to test statistical reliability. However, it is difficult to get the individual farm-level data needed for the econometric model. And even if farm-by-farm data are available, there rarely is enough variation in levels of ozone exposures and crop yields to produce significant statistical relation between these two.

Many of the recent studies of agricultural damages incorporate the biological response data generated by the National Crop Loss Assessment Network (NCLAN), which the Environmental Protection Agency (EPA) initiated in order to improve the state of knowledge regarding the impact of air pollution on agricultural production. Between 1980 and 1986, NCLAN researchers investigated 14 crops at sites across the U.S. in a total of 41 studies. This program involved field experiments with major agricultural crops to develop dose-response relationships between crop yields and ozone pollution (Lesser et al., 1990), and to develop estimates of the economic impact of these reduced yields (Adams et al., 1984).

All of the studies that we review here estimated crop damages due to ambient pollution from all sources; none of them estimated damages and costs due to motor-vehicle air pollution alone. We will estimate the agricultural cost of all anthropogenic air pollution too, but also will use a simple emissions-allocation model, discussed in Report #16, to isolate the contribution of motor vehicles to overall ozone air quality. Then, we will estimate the increase in crop output and consumer and producer welfare of a 10% reduction and a 100% reduction in emissions of ozone precursors due to motor-vehicle use. We will model 1990 conditions (air quality, emissions, and crop production), and express our results in 1991 dollars.

12.3.2 Review of major studies (see Table 12-1)

1). Adams et al. (1982) use a price-endogenous mathematical programming model to estimate the economic benefits of eliminating ambient oxidant exposure for 14 annual crops in Southern California in 1976. Their results indicate that eliminating air pollution would result in a $45.2 million increase in total economic welfare. The major contribution of this paper is the incorporation of endogenous prices into the model. (Previous research often assumed invariant exogenous prices). Their mathematical programming model incorporates a price-forecasting equation for each crop, and hence is able to model changes in market prices as a function of changes in production (due to changes in air pollution). This is important because, as indicated in Figure 1, pollution affects prices as well as output, and in order to estimate the true welfare effects of pollution, both effects must be modeled. However, Adams et al. (1982) do not allow for input substitutions, such as water, labor and machinery, in the production processes. Also, the authors note that the scientific data used in their model are weak.

2). Brown and Smith (1984) use a linear programming model to estimate the magnitude of the shift in acreage would occur among corn, soybeans and wheat on a set of Indiana farms if ozone were reduced to background levels. They find that because acreage shifts are likely to affect mainly farm income, the result of ignoring the effect of acreage substitution on farm income should indicate the magnitude of the problem of ignoring such substitutions in general. Because the then-current estimates of physical yield losses were insufficient for their purposes, they considered three arbitrary yield-change scenarios and found that if a reduction in ozone causes a big increase yield (i.e. corn yields increase 15 percent, soybeans 26 percent, and wheat 10 percent), then farm income will increase between 8 and 20 percent, depending upon the region. If there is only a small change in yield, then there will be no effect on farm income. These results demonstrate that substitution can have significant effects and so generally should not be ignored.

3). Mjelde et al. (1984) use the duality between production and profit functions, rather than mathematical programming, to identify the effects of ambient ozone concentrations on the output, profitability, and demand for variable inputs in Illinois. They find that a 10 percent increase in ambient ozone concentration levels would have reduced producer profits by $226 million in Illinois in 1980. As discussed above, this sort of econometric models has some advantages (but also some disadvantages) compared to mathematical programming models.

4). Garcia et al. (1986) use annual data on crop output, expenditures for inputs, levels of capital stocks at cash grain farms in Illinois, and ozone measurements (from the EPA) to perform an econometric analysis similar to the duality approach of Mjelde et al. (1984). The data set includes 229 farms for the years 1978 to 1981. However, their econometric model assumes constant prices regardless of production levels — an assumption that is inappropriate for an analysis at the aggregate agricultural market level. The variations in crop production attributable to changes in ozone concentrations can affect crop prices and hence the benefits of ozone reduction.

5). Howitt et al. (1984) use a mathematical programming model to estimate the economic impact of various ozone concentrations on 13 California crops during 1978. In order to incorporate the effects of price changes and crop and input substitutions that will result from changes in ambient ozone levels, they use a nonlinear programming model that recognizes the interdependence of cropping activities. The dose-response data are derived from the NCLAN program. The authors conclude that the effects of ozone on agriculture are substantial for both producers and consumers, but that producers bear most of the costs. They also note that price changes, and the substitution of crops and inputs, are important and should not be ignored.

6). Adams et al. (1984, 1985, 1986) use a mathematical programming framework to estimate the economic effects of changes in ambient ozone on U.S. agriculture for 1980. They derive their estimates by incorporating dose-response functions developed by the NCLAN into a spatial equilibrium model of U.S. agriculture. This model includes not only crop and livestock production, but also processing and export uses.

7). Adams and McCarl (1985) use a price-endogenous mathematical programming model to evaluate the economic consequences of ozone on agriculture in the "Corn Belt" states (Illinois, Indiana, Iowa, Missouri, and Ohio). The study includes four varieties of corn, seven varieties of wheat, and seven varieties of soybeans. (The Corn Belt states account for over half of U.S. production of corn and soybeans, and about 8% of U.S. wheat production.) The response of crop yields to ozone are estimated on the basis of data from NCLAN. Their results (Table 12-1) suggest that a 33 percent reduction in the ozone standard (from 0.12 to 0.08 parts per million [ppm]) would generate a $0.7 billion benefit, and that a 33 percent increase (from 0.12 to 0.16 ppm) in the ozone standard would yield a loss in excess of $2.0 billion. Interestingly, they find that the estimated benefits are not very sensitive to plausible variations in the parameters in the dose-response functions. They conclude by noting that "even a limited set of crop-response data, when generated in accordance with the needs of those doing the assessments, appears adequate to measure the general benefits of pollution control" (Adams and McCarl, 1985, p. 274). This is consistent with the results of Adams et al. (1984), who use a Bayesian approach to demonstrate that the policy value of additional plant-science yield response information declines rapidly.

8). Energy and Resource Consultants (1985) estimate the economic impact of ozone and sulfur dioxide pollution on agricultural production in the San Joaquin Valley of California in 1978. They perform a regression analysis on crop yields and air pollution, and find that a conservative estimate of the economic impact of air pollution on crop production is over $117 million. Over 98 percent of this is attributed to ozone. The economic losses from exceeding the California hourly ozone standard of 10 parts per hundred million are $106 million.

9). Kopp et al. (1985) estimate the impact of ozone in a model more firmly linked than are others to neoclassical theory of producer behavior. They evaluate the change in welfare that would occur under six alternative ozone standards ranging from 0.09 to 0.15 ppm. (The current U.S. National Ambient Air Quality Standard is 0.12 ppm). Some of their results, shown in Table 12-1, are similar to those of Adams and McCarl

(1985). They claim that in order to use available experimental biological dose-response information, such as that provided by NCLAN, one must assume that changes in air pollution do not affect the technologies of production, and that producers do not switch crops in response to yield changes due to ozone. They also note that even though this assumption is not realistic, their results would not be much different without it. (By contrast, Brown and Smith (1984) and Howitt et al. (1984) find that crop substitution *is* important.)

10). Rowe and Chestnut (1985) use the model of Howitt et al. (1984) to estimate the economic impacts of ozone and sulfur dioxide on 33 crops in the San Joaquin Valley of California in 1978. The work of Rowe and Chestnut (1985) differs from that of Howitt et al. (1984) in three major ways. First, Rowe and Chestnut (1985) use field data regression techniques (rather than chamber studies) to estimate yield losses. Second, they include important perennial crops, such as grapes. Finally, they consider three scenarios, which they deem to be more relevant to policy making: (1) a 50 percent reduction in the number of hours when ozone exceeds 10 pphm (part per hundred million), which roughly corresponds to the effect that a 12 pphm standard would have[6]; (2) meeting the current California State standard of 10 pphm for ozone and holding daytime sulfur dioxide levels constant; and (3) meeting an ozone standard of 8 pphm and holding daytime sulfur dioxide levels constant. They find that the statewide benefits that result from these scenarios are $42.6 million, $105.9 million, and $117.4 million, respectively.

11). Krupnick and Kopp (1988) use a price-endogenous mathematical programming model to estimate the economic benefits of ozone control for 1986. They estimate the benefits of 10, 25, and 50 percent reductions in ambient ozone for each state. Their results are summarized in Table 12-1.

12). Olszyk et al. (1988a) use published yield-loss equations to estimate the 1984 production losses for 20 crops. To calculate losses, they compare current ambient ozone levels with a base case under which ozone levels are reduced to a "clean air" background concentration of 0.025 ppm for 12 hours or 0.0272 ppm for 7 hours. Eight of the crops in their analysis have an estimated loss greater than five percent. The remaining 12 crops experience losses under five percent. They do not quantify the economic impacts of these losses.

13). The work of Adams et al. (1989) is conceptually similar to that of Adams et al. (1985), but uses an updated and more robust model of the economic impact of tropospheric ozone on agriculture. Whereas the earlier works are based on preliminary NCLAN data, the more recent paper takes advantage of the final results of the plant science and ozone data from the completed NCLAN program. Their estimates of economic benefits of ozone control for eight crops are summarized in Table 12-1.

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[6] They state "Scenario 1. Fifty percent reduction in the number of hours when O_3 is greater than or equal to 10 pphm. This is representative of typical ambient concentrations in the SJV during 1970-81 and is roughly consistent with a 12 pphm standard (11-13 depending upon the location)."

14). Howitt and Goodman (1989) use a positive mathematical programming approach estimate the effects of yield losses due to ozone in California during 1984. The positive programming approach is unique in the literature; it allows each regional cropping pattern to be exactly calibrated to the base-year data without additional constraints that would inhibit response to changes in ozone scenarios. The model used to simulate California's agricultural sector is an updated version of that used in Howitt et al. (1984). The model includes 17 production regions in California and 43 annual and perennial crops. Seven scenarios are considered: six in which the seasonal 12-hour mean ozone level is between 0.025 and 0.06 ppm, and one which evaluates a 0.10 ppm hourly standard. Depending upon the scenario considered, total benefits to California varied between $50 and $333 million annually and were divided approximately equally between producers and consumers.

12.4 THE MODEL

12.4.1 Overview

We model the net agricultural benefits of three pollution-reduction scenarios:

I) eliminate 100% of anthropogenic emissions of ozone precursors (VOCs and NO_X)
IIA) eliminate 10% of motor-vehicle related emissions of ozone precursors;
IIB) eliminate 100% of motor-vehicle related emissions of ozone precursors.[7]

For most of the remainder of this report, we will for simplicity refer to scenarios IIA and IIB together as scenario II.

A summary of the calculation procedure follows; details are provided in subsequent sections. First we, use an optimization model to estimate the welfare changes due to ozone air pollution the markets for eight major crops. We will refer to this agricultural optimization model, for eight crops, as the AOM8. Then we use yield-loss functions and value of production to scale these estimated welfare changes to account for ozone damages to other crops. Then, we apply a simple scaling factor to account for damages from pollutants other than ozone.

In the detailed calculation based on the AOM8, the overall change in welfare as a result of a change in ozone is estimated as the sum of changes in producer surplus and consumer surplus, less changes in deficiency payments (eq. 12-1 to 12-4), in the markets for the eight crops. The changes in producer surplus and consumer surplus are estimated by solving a constrained surplus-maximization problem. Specifically, we

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[7] We emphasize that we are modeling the benefits due to the elimination of ozone precursor (specifically, VOC and NOx emissions). Because of the nonlinearity of our simple ozone-production function (Report #16), a 10% reduction in precursor emissions does not necessarily result in a 10% reduction in ambient ozone.

solve a constrained welfare-maximization problem (eq. 12-5a to 12-5b) to find the equilibrium input resource quantities (X_{jir}) that maximize total surplus (including deficiency payments) in the markets for the eight crops, subject to the resource constraints in each region (eq. 12-5b). Then we substitute these optimal X_{jir} into a production function (eq. 12-6a or 12-6b, depending upon the scenario considered) in order to estimate the equilibrium crop production levels (Q_{ir}) in each region. Then, we substitute the Q_{ir} into a demand function (eq. 12-7) in order to find the equilibrium national price P_i for each of the eight crops. We use baseline national data on prices, quantities, and demand elasticities (which are not the same as the calculated equilibrium price and quantity!) to estimate the intercept ($\delta_{i)}$ and slope (β_i) of the demand curve (eq. 12-8 and 12-9 respectively). With estimates of X_{jir}, Q_{ir} , P_i, β_i, and $\delta_{i,}$ and given values for resource costs (C_{ij}), we use eq. 12-2 and 12-3 to estimate producer surplus (including deficiency payments) and consumer surplus. Finally, as noted above, we deduct the deficiency payments (eq. 12-1b) because they are simply welfare transfers and do not affect net social welfare.

We do this calculation for actual ozone levels in 1990, for ozone at the natural background level, and for ozone at the level it would be if motor-vehicle-related emissions of ozone precursors were reduced by 10 percent and by 100 percent. We model the effect of the decrease in ozone as a shift in the production function: at lower ozone levels, more output is obtained from a given set of inputs. The shift in the production function is estimated on the basis of dose-response functions for crops (eq. 12-11 to 12-13). The ozone data needed for the dose-response functions are either actual ozone readings in 1990, or modeled ozone assuming reductions in anthropogenic or motor-vehicle-related emissions.

The AOM8 is Howitt's (1991b) model of production and demand, with some additions and modifications by us. This model is a price-endogenous, self-calibrating, non-linear optimization program, similar in some respects to a computable general equilibrium (CGE) model. An advantage of this model over other national production models that uses mathematical programming techniques is its ability to calibrate exactly to empirical data[8]. In general, the model allows farmers to re-optimize their total agricultural production in response to ozone air pollution, subject to regional limits on resources, including land, water, and fertilizer, and calculates the change in consumer and producer surplus with respect to this adjusted optimum. However, the model does not allow for any technical change.

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[8] According to Howitt (1991b), it is difficult to calibrate most other mathematical programming models of agricultural resources without using strong constraints. Howitt's 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 one percent 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, 1991b).

The AOM8 includes eight major crops, which in 1990 accounted for 63% of the total value of agricultural production (Table 12-3). 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 (see Appendix A), we cannot ignore ozone damages to them. We estimate the ozone damages to all of the crops *not* included in the AOM8 on the basis of their ozone sensitivity, ozone exposure, and value of production relative to the ozone sensitivity, ozone exposure, and value of production of the eight crops included in AOM8. We do this for each of the 10 most valuable crops not included in AOM8, and for the category "all remaining crops."

Although this method does not explicitly account for changes in consumer surplus, or the effects of crop substitution, neither does it assume that there are no such effects. Rather it assumes, in a manner of speaking, that whatever these effects (expressed as the difference between welfare changes computed by the AOM8, and simple damages calculated by multiplying the yield-loss fractions by the 1990 value of production for each of the eight crops), they are the same in the markets for the crops not included as in the AOM8 as in the markets for the eight crops included in the AOM8.

Finally, we also apply a minor scaling factor to account for damage from pollutants other than ozone.

In the following sections, we discuss these steps formally. We will begin with the calculation of the change in social welfare (net benefits) in the market for the eight major crops, as a result of a change in ozone levels.

12.4.2 The welfare effects of changes in agricultural production, in the markets for eight major crops

As explained above, the total welfare effect, or net benefit, of a reduction in ozone air pollution is equal to the change producer surplus (PS) plus the change in consumer surplus (CS) less the deficiency payments. We estimate the welfare change in the markets for the eight major crops in each of 12 regions of the United States (the regions are described in Table 12-2), and then add the regional subtotals to get the U.S. total. Formally:[9]

$$\Delta W_{USA\,8} = \sum_{r=1}^{12} \Delta W_r \qquad \textbf{[12-1a]}$$

$$\begin{aligned} \Delta W_r &= \Delta PS_r + \Delta CS_r - \Delta DEFPMT_r \\ &= \sum_i (PS_{ir}^b - PS_{ir}^o) + (CS_{ir}^b - CS_{ir}^o) - (DEFPMT_{ir}^b - DEFPMT_{ir}^o) \end{aligned} \qquad \textbf{[12-1b]}$$

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[9] For notational simplicity, we have omitted the usual asterisk superscript (*) that indicates "equilibrium". Also, where we do not indicate a superscript b or o, we mean that the equation applies to both cases.

where:

$$PS^{o}_{ir} = P^{o}_{i}Q^{o}_{ir} + DEFPMT^{o}_{ir} - MKC^{o}_{ir} - \sum_{j} HPC^{o}_{jir} - \sum_{j} VIC^{o}_{jir} \qquad \textbf{[12-2a]}$$

$$PS^{b}_{ir} = P^{b}_{i}Q^{b}_{ir} + DEFPMT^{b}_{ir} - MKC^{b}_{ir} - \sum_{j} HPC^{b}_{jir} - \sum_{j} VIC^{b}_{jir} \qquad \textbf{[12-2b]}$$

and

$$CS^{o}_{ir} = \tfrac{1}{2} \cdot (\delta_i - P^{o}_{i}) \cdot Q^{o}_{ir} \qquad \textbf{[12-3a]}$$

$$CS^{b}_{ir} = \tfrac{1}{2} \cdot (\delta_i - P^{b}_{i}) \cdot Q^{b}_{ir} \qquad \textbf{[12-3b]}$$

and:

$$DEFPMT_{ir} = DP_{ir} \cdot Q_{ir} \qquad \textbf{[12-4a]}$$

$$MKC_{ir} = Q_{ir} \cdot MKTGCST_{ir} \qquad \textbf{[12-4b]}$$

$$HPC_{jir} = (X_{jir})^{2} \cdot HEDCST_{jir} \qquad \textbf{[12-4c]}$$

$$VIC_{jir} = X_{jir} \cdot C_{jir} \qquad \textbf{[12-4d]}$$

(where the superscripts o and b have been omitted for economy of exposition)

and

Superscript o = “initial” ozone levels: actual levels in 1990 (estimated from data taken at ambient air-quality monitors, discussed in section 12.4.6),

Superscript b = ozone levels after either:

I) all anthropogenic ozone precursor emissions is eliminated, so that ozone is reduced to the natural background level,

or

II) 10% or 100% of emissions of ozone-precursor pollutants from motor vehicles are eliminated (discussed below).

Subscript i = major crop i (corn, cotton, wheat, barley, alfalfa, soybeans, rice, sorghum; in 1990, these eight crops accounted for 63% of the total value of U.S. agricultural production[10] [Table 12-3])

Subscript j = input j (land, water, capital, nitrogen, and pesticides)

Subscript r = 12 agricultural regions of the United States (Table 12-2)

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[10] Howitt’s (1991b) model also includes oats, but because we were unable to locate a dose-response function for oats, we do not include it in our welfare estimates. We leave oats in the production model, but we assume that there is no change in oat production due to ozone pollution. (Because the value of oat production is relatively low -- about $0.5 billion -- this treatment probably is quite adequate.)

ΔW_{USA8} = increase in total economic welfare (net dollar benefits), in the markets for the eight major crops, in the U.S.A. due to a reduction in ambient ozone concentrations from 1990 levels o to background levels (case I) or levels without 10% or 100% motor-vehicle-related ozone precursor emissions (case II)

ΔW_r = increase in total economic welfare (in the markets for the eight major crops) in region r due to a reduction in ambient ozone concentrations from 1990 levels o to background levels (b case I) or levels without 10% or 100% of motor-vehicle-related ozone precursor emissions(b case II)

ΔPS_r = increase in producer surplus, or profits, in region r due to a reduction in ambient ozone concentrations from 1990 levels o to background levels (b case I) or levels without 10% or 100% of motor-vehicle-related ozone precursor emissions(b case II)

ΔCS_r = increase in consumer surplus in region r due to a reduction in ambient ozone concentrations from 1990 levels o to background levels (b case I) or levels without 10% or 100% of motor-vehicle-related ozone precursor emissions(b case II)

PS_{ir} = producer surplus from crop i in region r, estimated at actual ozone levels in 1990 ($PS_{ir}{}^{o}$), and reduced ozone levels ($PS_{ir}{}^{b}$, cases I and II) (note that the producer surplus includes the deficiency payments, which are made to producers)

CS_{ir} = consumer surplus crop i in region r, estimated at actual ozone levels in 1990 ($CS_{ir}{}^{o}$), and reduced ozone levels ($CS_{ir}{}^{b}$, cases I and II)

$DEFPMT_{ir}$ = total deficiency payments for crop i in region r, estimated at actual ozone levels in 1990 ($DEFPMT_{ir}{}^{o}$), and reduced ozone levels ($DEFPMT_{ir}{}^{b}$, cases I and II) (see section 12.2.2 for a discussion)

MKC_{ir} = marketing costs for crop i in region r, estimated at actual ozone levels in 1990 ($MKC_{ir}{}^{o}$), and reduced ozone levels ($MKC_{ir}{}^{b}$, cases I and II) (discussed below)

HPC_{jir} = hedonic program cost for input j for crop i in region r, estimated at actual ozone levels in 1990 ($HPC_{jir}{}^{o}$), and reduced ozone levels ($HPC_{jir}{}^{b}$, cases I and II) (discussed below)

VIC_{jir} = variable input cost for input j for crop i in region r, estimated at actual ozone levels in 1990 ($VIC_{jir}{}^{o}$), and reduced ozone levels ($VIC_{jir}{}^{b}$, cases I and II) (discussed below)

Q_{ir} = the equilibrium quantity of crop i in region r, estimated at actual ozone levels in 1990 ($Q_{ir}{}^{o}$), and reduced ozone levels ($Q_{ir}{}^{b}$, cases I and II) (these are defined by the production function, given in eq. 12-6)

P_i = the equilibrium national price of crop i, estimated at actual ozone levels in 1990 ($P_i{}^{o}$), and reduced ozone levels ($P_i{}^{b}$, cases I and II) (based on the aggregated national quantity of crop i, and defined by the demand eq. 12-7; note that this is national price, not a regional price; also, it is not the same as the "baseline" national price used to calibrate the model, discussed below)

DP_{ir} = deficiency payment, per unit of output, for crop i in region r, assumed to be independent of ozone levels (see section 12.2.2 and below for a discussion)

$MKTGCST_{ir}$ = the marketing cost, per unit of output, for crop i in region r, assumed to be independent of ozone levels (see discussion below)

$HEDCST_{jir}$ = the hedonic program costs, per unit of output for input j for crop i in region r. The are assumed to be independent of ozone levels.

C_{jir} = the constant resource cost of input j in producing crop i in region r (Howitt, 1991b)

X_{jir} = the optimal use of input j in producing crop i in region r, estimated at actual ozone levels in 1990 (X_{jir}^o), and reduced ozone levels (X_{jir}^b, cases I and II) (this is the variable with respect to which welfare is maximized)

δ_i = the intercept of the national demand curve for crop i with the price axis (eq. 12-9)

12.4.3 The objective function and the equilibrium quantities of inputs X_{jir}

In order to calculate the change in CS and PS, we must know: i) the equilibrium crop prices and quantities at the different ozone levels, ii) the average resource costs of production; and iii) the intercept of the demand curve. Once the production and demand functions are defined, computing economic welfare measures is straightforward.

The AOM8 maximizes producer surplus and consumer surplus in the markets for the eight major crops. (Maximizing this objective function is identical to solving the competitive equilibrium problem.) Producer plus consumer surplus is equal to the area under the demand curve less costs (refer to Figure 12-1, and discussion above). Thus, the objective function is defined as the area under the demand curves, plus deficiency payments, less marketing costs, hedonic program costs, and variable input costs. Formally (in the following, we omit the superscripts *o* and *b*, for simplicity of exposition):

Maximize producer surplus and consumer surplus in the markets for the eight major crops:

$$\underset{X_{jir}}{\text{Max}}\ PS + CS = \underset{X_{jir}}{\text{Max}}: \qquad \textbf{[12-5a]}$$

$$\sum_i \{[\,\delta_i - \tfrac{1}{2}\beta \sum_r Q_{ir}] \sum_r Q_{ir}\} \qquad \text{Area under the demand curves (from eq. 12-7)}$$

$$+\ \sum_i \sum_r Q_{ir} \cdot DP_{ir} \qquad \text{plus Deficiency Payments (DEFPMT, from eq. 12-4a)}$$

$$-\ \sum_i \sum_r Q_{ir} \cdot MKTGCST_{ir} \qquad \text{less Marketing Costs (MKC, from eq. 12-4b)}$$

$$-\ \sum_j \sum_i \sum_r X^2_{jir} \cdot HEDCST_{jir} \qquad \text{less Hedonic Program Costs (HPC, from eq. 12-4c)}$$

$$-\ \sum_j \sum_i \sum_r X_{jir} \cdot C_{jir} \qquad \text{less Variable Input Costs (VIC, from eq. 12-4d)}$$

subject to input constraints:

$$\sum_i X_{jir} \le B_{jr} \qquad \text{for all j inputs in each region r} \qquad \textbf{[12-5b]}$$

where:

$$Q^o_{ir} = A_i X_{1ir}^{\alpha_{1i}} X_{2ir}^{\alpha_{2i}} \ldots X_{5ir}^{\alpha_{5i}} \qquad \text{for all i,r} \quad \textbf{[12-6a]}$$

$$Q^b_{ir} = \left(1 + \frac{QGAIN\,\%_{ir}}{100}\right) \cdot Q^o_{ir} = \left(1 + \frac{QGAIN\,\%_{ir}}{100}\right) \cdot (A_i X_{1ir}^{\alpha_{1i}} X_{2ir}^{\alpha_{2i}} \ldots X_{5ir}^{\alpha_{5i}}) \quad \text{for all i,r} \qquad \textbf{[12-6b]}$$

where:

B_{jr} = the constraint for input j in region r (Howitt, 1991b)
A_i = crop-specific constant in the Cobb-Douglas production function (estimated from a baseline set of crop and input price and quantity data; see below). This parameter is the same for all regions.
α_{ji} = elasticity of production of crop i with respect to input of resource j (estimated from a baseline set of crop and input price and quantity data; see below). This parameter is the same for all regions.
QGAIN%$_{ir}$ = the percentage change in yield of crop i resulting from a reduction in ambient ozone concentrations from level o to level b in region r (eqs. 12-10 and 12-11, derived below; the results for case I, reduction to natural background, are shown in Table 12-5),
β_i = the slope of the national demand curve for crop i (eq. 12-8).

All other parameters are defined above.

Deficiency payments. Deficiency payments (eq. 12-4a) were the result of a federal crop-price support program.[11] In 1990, farmers had the option of enrolling

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[11] This program no longer exists, but we include it in the analysis because it was in effect in 1990, which is the year of our analysis.

acreage in this program. Crops produced from fields enrolled in the program were guaranteed a minimum price, such that if the market price dropped below this minimum, the federal government compensated the farmers for the difference. In the model, deficiency payments are defined as the difference between the base price for those crops enrolled in the program and those crops which were not. We assume that the deficiency payment per unit of output is the same in all four of our scenarios.[12]

Note that the objective function (eq. 12-5a), with which we maximize surplus in the crop market, includes deficiency payments, but that the calculation of the change in social welfare or net benefits, in eq. 12-1b, excludes these deficiency payments. Deficiency payments are a part of the objective function because, in 1990, they were a real part of the market and had a direct impact on growers' planting decisions. In order to estimate the appropriate equilibrium prices and quantities for the market as it actually was structured in 1990, we must include price subsidies in the objective function. However, once we have the estimated prices and quantities, and turn to calculate the change in social welfare, we back out the deficiency payments (in eq. 12-1b), which are transfer payments, and not real welfare gains.

Hedonic program costs. Although the price-subsidy program offered farmers a higher expected price and reduced risk, they did not enroll all of their acreage in the program. This implies that enrollment had a cost, which increased with increasing acreage enrollment. To account for this, Howitt's (1991b) model includes a "hedonic program cost" (eq. 12-4c). There are four components of this hedonic cost. First, the price-support program could require that land be set aside, or idled. The cost of idling land was the foregone returns to crop production. Second, the program could place a limit on the crop yield. The cost of this limit was the foregone returns to the extra output from higher yielding land. Third, in some areas, maintaining the base acreage allotment may have involved costs. Finally, enrolling in programs may have involved other "intangible costs" (Howitt, 1991b).

Regional marketing costs. The cost of transporting and marketing crops differs from region to region, with the result that regional prices differ from the national-average weighted price that we calculate. In Howitt's model the parameter $MKTGCST_{ir}$ is not the absolute marketing cost for crop i in region r, but rather the difference between the regional cost and the national-average cost. This difference is estimated as the difference between the baseline national price and the baseline regional price:

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[12] Although the guaranteed price itself might have been a function of ozone levels and crop output, the difference between the guaranteed price and the market price might have remained nearly constant. For example, it is likely that, if ozone had been reduced, and crop output thereby increased and market prices thereby reduced, the Federal government would have guaranteed a lower support price, such that the difference between the market price and the guaranteed price might have been unchanged.

$$MKTGCST_{ir} = \frac{MKC_i^R}{Q_i^R}$$

$$MKC_{ir}^R = P_i^N \cdot Q_i^R - P_i^R \cdot Q_i^R$$

$$MKTGCST_{ir} = \frac{P_i^N \cdot Q_i^R - P_i^R \cdot Q_i^R}{Q_i^R} = P_i^N - P_i^R$$

Note:

$$P_i^N = \frac{\sum_R P_i^R \cdot Q_i^R}{\sum_R Q_i^R}$$

where:

the superscript R = the baseline (not estimated) regional price or quantity
the superscript N = the baseline (not estimated) national-average
MKC_i^R = the baseline marketing cost for crop i in region R
Q_i^R = the baseline (not estimated) quantity of crop i in produced in region R
P_i^N = the baseline (not estimated) national-average price of crop i
P_i^R = the baseline (not estimated) price of crop i in region R
all other terms as defined above

Keep in mind that the baseline data are not the same as the modeled result. The baseline data are actual production and output data for a given crop, region, and year, and are used to calibrate the model.

Note that the sum over all regions of the *baseline* MKC_i^R equals zero, because the negative increments cancel the positive increments. However, the sum of the *modeled* MKC_{ir} (in eq. 4b) will not necessarily equal zero. Because of this, and because the MKC_{ir} term (eq. 4b) is needed for regional estimates, it is included in the model.

In Howitt's model, the parameter $MKTGCST_{ir}$ is a constant, independent of output and ozone levels. This assumption probably is reasonable for small changes in price and quantity.

The solution to the maximization problem. Equations 12-6a and 12-6b are standard Cobb-Douglas regional production functions. For each region, the values of α_{ji} and A_i are estimated through a calibration procedure, which requires a baseline set of crop production and prices. Howitt (1991b) uses Bureau of the Census (1989) for the baseline regional crop production data (see section 12.4.7). For further details on the estimation techniques, see Howitt (1991b).

The first order conditions for this problem are solved simultaneously in the usual manner to produce estimates of the optimal regional input use (X_{jir}). Once the optimal X_{jir} are estimated, computing the equilibrium quantities (Q_{ir}) is straightforward; we simply substitute the equilibrium X_{jir} back into the production function (eq. 12-6a for case I, and eq. 12-6b for case II). Equilibrium prices can then be calculated using eq. 12-7:

$$P_i = \delta_i + \beta_i \sum_r Q_{ir} \qquad \text{for all i} \qquad \textbf{[12-7]}$$

We then use eq. 12-1 through 12-4 to estimate the welfare changes. (See eq. 12-8 and 12-9 for the derivation of δ_i and β_i).

Note that we go through this procedure four times, for four different ozone/crop production scenarios: once for Q_{ir}^{o}, the regional production function under 1990 ozone conditions[13]; once for Q_{ir}^{b}, case I, the regional production function given a reduction in ozone to background; and twice for Q_{ir}^{b}, case II, the regional production function given a reduction in ozone to the level with 10% or 100% of motor-vehicle related emissions eliminated. As shown in eq. 12-6b, we assume that for any crop, a given change in ozone causes a constant percentage change in output *for any combination of inputs.*[14] Thus, we simply shift the original production function from Howitt (1991b) by the percentage change in output corresponding to the assumed change in ozone. The percentage change in output resulting from a change ozone — the parameter QGAIN% — is calculated from dose-response functions, which are discussed below. Each of the four production conditions (Q_{ir}^{o}, Q_{ir}^{b} case I, and Q_{ir}^{b} cases IIA and IIB), which correspond to the four ozone conditions, result in a separate and unique set of optimal resource inputs, equilibrium prices, equilibrium quantities, and producer and consumer surplus measures.[15]

Model of agricultural demand. Recall from above that in order to estimate equilibrium prices and quantities, we need to know the slope and intercept of the

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[13] Note that because of the model calibration procedure used, the estimates produced for actual 1990 ozone conditions should be very close to the baseline quantities and prices.

[14] Ideally, we would want to treat ozone as another input in the production function.

[15] The demand equation (discussed below), and the parameters B_{jr} (the resource constraint for input j in region r), C_{jir} (the constant resource cost of input j in producing crop i in region r), A_i (crop-specific constant in the Cobb-Douglas production function), DP_{ir} (the deficiency payment per unit), $MKTGCST_{ir}$ (the marketing cost per unit), $HEDCST_{jir}$ (the hedonic program cost), and α_{ji} (elasticity of production of crop i with respect to input of resource j) are assumed to be independent of ozone levels.

demand curve for each crop. According to Howitt (1991b, p. 16), "commodity demand functions are linear and quantity dependent, which implies that total revenue is a quadratic function of the total national production... Calibration of the demand slope and intercept coefficients uses a well known method of weighting the base-year regional prices by output levels to get a weighted national price." Thus, Howitt (1991b) estimates a single national demand curve for each crop, on the basis of baseline quantity-weighted national-average prices, and national production. Formally, the slope of the national demand curve for each crop is defined as:

$$\beta_i = \frac{P_i^N \eta_i}{Q_i^N} \qquad \textbf{[12-8]}$$

where:

β_i = the estimated slope of the national demand curve for crop i
η_ι = elasticity of national demand for crop i in the base year (see Table 12-6)
P_i^N = the weighted-average national (superscript N) baseline price of crop i [16]
Q_i^N = the aggregate national (superscript N) baseline quantity of crop i

Given the slope β_i,, the demand intercept δ_i can be computed by expressing the linear demand eq. 12-7 in terms of δ_i :

$$\delta_i = P_i^N - \beta_i Q_i^N \qquad [12\text{–}9]$$

Three points are important here. First, P_i^N and Q_i^N are baseline national aggregated quantities which are used to estimate the slope and intercept of the demand curve; they are not the same as the estimated equilibrium quantities from eq. 12-5 and 12-6. Second, Howitt (1991b) estimates a national, not regional, demand function, even though baseline price and quantity data are available at the regional level, because the demand elasticities are not known at the regional level. Third, ozone pollution changes the level of consumption, but not the demand curve per se, which is independent of the cost variables including pollution. Hence, we use the one set of demand equations for all ozone levels.

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[16] These baseline national figures for prices and quantities are used only to derive estimates of the coefficients in the demand equations (β_i and δ_i). The estimated national equilibrium price and regional quantities are used to calculate consumer surplus and producer surplus.

12.4.4 Accounting for ozone damages to other crops, damages from other pollutants, and other effects

With the AOM8 and the procedure just described, we estimate in detail ozone damages to eight major crops, which together account for some 63% of the total value of U.S. agricultural production (Table 12-3). 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, and damages to all crops from other pollutants. As we shall see, ozone damages to the crops not included in the AOM8 are likely to be substantial, because the crops not included are exposed to at least as much ozone, and are at least as sensitive to ozone, as are the crops included.

In general, as we have seen, the welfare effect of pollution in the crop market 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 (which determines consumer surplus), and the constrained ability of producers to reallocate resources to less sensitive crops in order to maximize profits. 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 something like Howitt's (1991b) optimization model. For the crops not included in Howitt's model, 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 (this is determined by the elasticity of demand), 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 (cost = crop price multiplied by quantity lost due to ozone) 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: as regards 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 as regards 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 by a version of the AOM8 for the other crops) to the simple change in market value is the same as this ratio as calculated with the AOM8 for the eight crops. 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:

$$\Delta TW_{USA} = \Delta W_{USA\,8} \cdot \left(1 + \frac{YLV_{OC}}{YLV_{8C}}\right) \cdot SFOP$$

$$YLV_{OC} = \sum_{o} VP_{o} \cdot \frac{Q_{o,PP}}{Q_{o,PI}} \qquad \textbf{[12-10]}$$

$$YLV_{8C} = \sum_{i} VP_{i} \cdot \frac{Q_{i,PP}}{Q_{i,PI}}$$

where:

ΔTW_{USA} = 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 as defined above
YLV = the yield-loss value of ozone damage to crops
VP = the value of crop production in 1990 (Table 12-3)
SFOP = scaling factor to account for damages from pollutants other than ozone (estimated to be 1.05 to 1.10; see below)
Q_{PP} = yield loss function for background ozone levels PP (Table 12-4; section 12.4.5)
Q_{PI} = yield loss function for initial ozone levels PI in 1990 (Table 12-4; section 12.4.5)
subscript OC = crops other than the eight included in the AOM8
subscript 8C = the eight crops included in the AOM8
subscript o = crop o not included in the AOM8
subscript i = crop i included in the AOM8

Table 12-3 shows the value of production of the eight crops included in the AOM8, the value of production of the 10 most valuable crops not included, the value of production of the remaining crops, and the top producing states for each crop. We can see that most of the crops included in the AOM8 are produced in the Midwest, whereas the crops not included are more widely produced, but with a tendency to be concentrated in California: California is a major producer of several of the 10 most valuable crops not included, and the major producer of all of the remaining crops. After California comes Florida.

The yield-loss functions, shown in Table 12-4, require an estimate of the ambient ozone air quality in the regions where the crops are produced. This is discussed in section 12.4.6. Here, we 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.

Damages to all crops from other pollutants. 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 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) (Herrick and Kulp, 1987) gaseous SO_2 and NO_2 had a negligible impact on crops in the United States.

Ashmore (1991) states that barley, clover, and lucerne are especially sensitive to SO_2. However, clover and lucerne are minor crops. Moreover, SO_2 also can 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 U. S. (Herrick and Kulp, 1987, p. I-25). Adams et al. (1986) estimated that a 10% to 50% increase in acid deposition would cost $19 to $140 million (1980 dollars) in losses in the market for soybeans, the only crop found to be sensitive to acid deposition. (See also Spash [1997].) This is more than an order of magnitude smaller than the impacts of a 25% change in ozone (Table 12-1). Moreover, when Adams et al. (1986) included fertilization effects -- additional expense for lime, to reduce acidity, but less expense for nitrogen fertilizer, 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)[17]. 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.

Other issues. 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.

12.4.5 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-bound 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 U.S. in 1990. The county-by-county 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.

Sources of data. The data necessary to estimate dose-response functions can come from tests in open fields or open-top chambers, or from econometric methods. Most data come from tests in open-top chambers.

Open-field systems are large experimental field units on which ozone concentrations are controlled by a series of pipes that emit ozone precursors (nitrogen oxides and hydrocarbons) (Laurence et al., 1982). It is difficult to control ozone levels in

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[17] 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 5 times the present ambient concentrations would harm plant growth, at least in the short run.

these systems because the levels are affected strongly by ambient factors such as wind and temperature. It also is hard to achieve less-than-ambient concentrations of ozone.

Econometric methods (Leung et al., 1982; Moskowitz et al., 1982) are based on relationships between ambient ozone concentrations and actual yields. Although this method estimates the yield responses under exact conditions, data for ambient ozone concentrations and actual yields often do not have sufficient variability to estimate statistically significant relationships.

The open-top chamber system has been widely employed to assess crop yield responses to ozone. Ozone precursors, such as nitrogen oxides and hydrocarbons, are injected into the chamber through an inlet to duplicate various ozone exposures. This method 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 through the use of this system and the data under ambient conditions is very small (Heck, Taylor, and Tingey 1988). Many studies have employed the open-top chamber system to assess crop yield responses to ozone (Olszyk et al., 1988; Heagle et al., 1986; McCool et al., 1986; Rowe and Chestnut 1985; Heck et al., 1984).

Functional form. Typically, researchers fit experimental or econometric dose-response data to a Weibull function (Heck et al., 1984):

$$Q = \mu \cdot e^{-(\frac{OZONE}{\gamma})^{\lambda}} \qquad \textbf{[12-11]}$$

where:

Q = the observed yield
OZONE = the ozone concentration in ppm (air quality data and estimates are discussed in section 12.4.6)
μ = the hypothetical maximum yield at zero ozone
γ = the ozone concentration when Q is 0.37μ
λ = a dimensionless shape parameter

This form is used because it is biologically realistic and generates an estimated yield that approaches zero as ozone concentrations increase to infinity (Heck, Taylor, and Tingey, 1988), 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.

In this study, we use published dose-response functions to assess the yield losses to crops from ozone in the United States. Most of the functions assume a Weibull functional 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-estimating and the high-estimating yield functions, and thereby establish low and high scenarios. Table 12-4 summarizes the dose-response functions for the eight crops in the AOM8, the ten most valuable crops not in the AOM8, and all other crops.

Application in the AOM8. With the functions shown in Table 12-4, the percentage yield change in each county c due to a reduction in ozone (QGAIN%) can be calculated as:

$$QGAIN\,\%_{ic} = \frac{Q_{ic}^{b} - Q_{ic}^{o}}{Q_{ic}^{o}} \cdot 100 \qquad \textbf{[12-12]}$$

where:

$QGAIN\%_{ic}$= the percentage change in the yield of crop i due to a reduction in ozone concentration from the 1990 levels (o) to lower levels (b), in County C

Q^{o}_{ic} = estimated yield of crop i under 1990 ozone levels (o) in County C (calculated by setting the parameter "OZONE" in eq. 12-11 equal to 1990 ozone levels in County C)

Q^{b}_{ic} = estimated yield of crop i in county C with either the natural background ozone level (case I) or ozone levels given a 10% or 100% reduction in motor-vehicle-related emissions (cases IIA and IIb) (calculated by setting the parameter "OZONE" in eq. 12-11 equal to estimated ozone levels in County C under emission-reduction scenarios I or II)

The yield responses are first calculated for each county. In order to aggregate the percentage changes from the level of the county to the level of the crop-production region (12 in the U.S.), the percentage changes must in effect be "weighted" by crop production in each county. Specifically:

$$QGAIN\,\%_{ir} = \frac{\sum_{c \in r} QGAIN\,\%_{ic} \cdot QB_{ic}^{o}}{\sum_{c \in r} QB_{ic}^{o}} \qquad \textbf{[12-13]}$$

where:

subscript r = crop-production region
subscript c = county
subscript i = crop
$QGAIN\%_{ir}$ = the percentage change in the yield of crop i due to a reduction in ozone concentrations from 1990 levels (o) to lower levels (b), in crop-production region r (results for case I, reduction to natural background, are shown in Table 12-5)
$QGAIN\%_{ic}$ is defined above for eq. 12-12

QB^{o}_{ic} = the baseline quantity of crop i produced in county C in 1990 (U.S. Department of Commerce, 1987; discussed in section 12.4.7)

Table 12-5 details the estimated low and high percentage yield changes ($QGAIN\%_{ir}$) for each of the eight crops in the AOM8, in the twelve regions of the U.S, assuming that ozone is reduced to the natural background level (case I). As discussed above, these percentage yield changes are used to shift the production-cost functions in the agricultural optimization model (see eq. 12-6). After shifting these functions, we recompute producer and consumer surplus to estimate the net change in economic welfare.

Application in the simple yield-loss estimates of damages. For the crops not included in the AOM8, we simply apply the yield-loss functions to total national value of production for each crop, as shown by eq. 12-10. Table 12-4 shows the function used. Appendix A discusses the results of some of the studies which generated the functions, and compares the ozone sensitivity of the crops not in the AOM8 with the sensitivity of the crops in the AOM8.

12.4.6 Air-quality modeling and data

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

$$\Delta E = f(\Delta P, O) = f(PI, PP, O) \qquad \textbf{[12-14]}$$

where:

ΔE = the change in the effect of interest (in this analysis, crop yield)
ΔP = the change in ambient air pollution
O = other variables
PI = the initial pollution level
PP = the pollution level after the change in pollution -- in this social-cost analysis, the level after removing all anthropogenic ozone-precursor emissions, or 10% or 100% of motor-vehicle related ozone-precursor emissions

We specify the initial pollution level, PI, to be the actual ambient air quality in each county or crop growing region of the U. S. 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:

$$\text{Assume}: \frac{PP_{O3}}{PI_{O3}} = \frac{PP_{O3}*}{PI_{O3}*}$$

[12-15]

$$PP_{O3} = PI_{O3} \cdot \frac{PP_{O3}*}{PI_{O3}*}$$

where:

PP_{O3} = the estimated actual ozone level after the change in ozone (eliminate all anthropogenic ozone-precursor emissions, or eliminate 10% or 100% of motor-vehicle-related ozone-precursor emissions)
PI_{O3} = the actual ambient ozone level in 1990 (data from air-quality monitors [EPA, 1993]; discussed below)
$\frac{PP_{O3}*}{PI_{O3}*}$ = the estimated ratio of ozone levels after the change in emissions to ozone levels given the baseline emissions (see Report #16 for details)

We model three different ozone-reduction scenarios (i.e., three different values of PP):

I) ozone reduced from 1990 levels to the natural background levels, with no anthropogenic emissions, and
II) ozone reduced from 1990 levels to the levels that would have resulted had
  A) 10% of motor-vehicle related ozone-precursor emissions had been eliminated, or
  B) 100% of motor-vehicle related ozone-precursor emissions had been eliminated.

In Report #16, we develop our estimate of $\frac{PP*}{PI*}$. Here, we summarize the main simplifying assumptions in our model.

It is most important to understand that 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 eq. 12-15, we estimate the *ratio* $\frac{PP*}{PI*}$; we do not estimate PI* and PP* individually in units of concentration ($\mu g/m^3$). We do this because we have a only crude model of pollutant dispersion and ozone formation which is not at all suited to estimating absolute concentrations of ozone, but which - we hope -- is serviceable for estimating the contribution of one pollution source (e.g. motor vehicles)*relative* to another source (e.g., power plants). And to estimate the ratio $\frac{PP*}{PI*}$, we need to know only the relative contribution to ambient ozone of the different emission sources.

The ratio $\frac{PP*}{PI*}$ can be estimated simply by assuming that it is equal to the ratio $\frac{PP'*}{PI'*}$, where PP'* and PI'* are the emitted pollutants associated with the ambient pollutants PP* and PI*. For example, one might assume that ozone levels are proportional to total VOC emissions (VOCs are one of the two main precursors of ozone, the other being NO_X), so that $\frac{PP_{O3}*}{PI_{O3}*}$ is equal to the ratio of total VOC emissions after the change in emissions to total baseline VOC emissions. This, in fact, is what the now-defunct Office of Technology Assessment assumed in its analysis of strategies for reducing urban ozone (U. S. Congress, 1989). But this has several shortcomings: first, NO_X emissions as well as VOC emissions contribute to ozone formation; second, the effect of VOCs depends on their ozone forming potential, which varies considerably across classes of compounds; and third, the contribution of different emission sources (motor vehicles, power plants, industry, etc.) to the ozone concentration at a particular receptor depends on the height, location, and other characteristics of the sources. Ideally, one would use a detailed, 3-dimensional, regional photochemical oxidant model of ozone formation, and estimate ozone levels with and without the precursor emissions from the sources of interest. But such models have been developed for only for a few regions of the U. S. (such as the Northeast, and Southern California), and are quite costly to calibrate and run. The application of such models is well beyond our scope.

We have chosen instead to estimate the ratio $\frac{PP_{O3}*}{PI_{O3}*}$ on the basis of a very simple model of precursor dispersion and ozone formation. 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. Specifically:

I). We assume 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[18] (AQCR) as county c. We distinguish between emissions generated within county c, and emissions generated in other counties within the same AQCR as c. We ignore the transport of pollution from one AQCR to another; i.e., we assume that air quality in a particular AQCR is a function only of emissions within the AQCR. Of

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

course, we recognize that for some pollutants in some areas, such as ozone in the Northeastern U.S., long-range transport is important, and ideally should not be ignored. However, we were unable to perform sophisticated inter-regional modeling for the entire U. S..

II). We assume 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 ignore meteorology and topography and assume that the ambient ozone is a function only of the amount precursor emissions at the site of the monitor. (We make these assumptions because we cannot easily model chemical transformations as a function of the distance from the source.) We assume that ozone formation is a nonlinear function of the amount of dispersion-adjusted NO_X and dispersion-adjusted and "reactivity"-weighted VOC (DRVOC):

$$PP_{O3} = f\left((DRVOCs)^{A} \cdot (DNO_x)^{B}\right) \qquad \textbf{[12-16]}$$

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 (see Report #16 in the social-cost series). Thus, combining equations 12-15 and 12-16, we estimate the change in ozone due to a change in motor-vehicle emissions as follows:

$$PP_{O3} = PI_{O3} \cdot \frac{(DRVOC_{\Delta E})^{0.55} \cdot (DNOx_{\Delta E})^{0.40}}{(DRVOC_{total})^{0.55} \cdot (DNOx_{total})^{0.40}} \qquad \textbf{[12-17]}$$

where:

$DRVOC_{\Delta E}$ = dispersion-adjusted, reactivity-weighted emissions of VOCs after the change in emissions ΔE (eliminate all anthropogenic pollution, or 10% or 100% of motor-vehicle pollution)

$DNOx_{\Delta E}$ = dispersion-adjusted emissions of NO_X after the change in emissions ΔE

$DRVOC_{total}$ = total dispersion-adjusted, reactivity-weighted emissions of VOCs from all sources, before the change in emissions ΔE

$DNOx_{total}$ = 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 Report #16 for details.

This "model" of ozone air quality obviously is quite crude, and probably only marginally better than simply assuming that ozone levels are proportional to VOC emissions. Most crude, and most problematic, 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* $\frac{PP^*}{PI^*}$, and not PI* and PP* individually in units of concentration ($\mu g/m^3$), and because of the nonlinear 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.

III). 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 EPA's complete emission inventory that involve activities related to the use of motor vehicles. These sectors include oil and gas extraction, petroleum refining, motor-vehicle manufacture, motor-vehicle service, steel production, road construction, and so on. 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 of sectors. We refer to these as "indirect" emissions. Details are given in Report #10 in the social-cost series. In the summary tables, results are reported with and without these indirect emissions.

Note that, when we estimate the ozone level after removing motor-vehicle related emissions, we estimate the effects of a specific, "marginal" change in pollution: the difference between actual ozone (PI) and, what ozone would have been had motor-vehicle-related ozone-precursor emissions been reduced by 10% or 100% (PP). Because ozone formation is a nonlinear function of two precursor pollutants, NO_X and VOCs, the only way to model the real nonlinear effect on ozone of motor-vehicle ozone-precursor emissions is to model actual ozone levels with and without motor vehicle precursor emissions.

Initial (1990) ozone air quality (PI_{O3}) in the AOM8. To specify the initial ozone levels, in the AOM8, we use actual data from EPA air-quality monitors (EPA, 1993). The EPA maintains hundreds of air-quality monitors throughout the U. S. The EPA classifies monitors according to general location (urban and city center, suburban, and rural), and land use (residential, commercial, industrial, agricultural, forest, desert, mobile, blighted area). There are thus three times eight equals twenty-four specific location/land-use monitor categories. Table 12-7 shows these 24 categories, and the number of counties with ozone monitors in each category[19].

Given this classification of monitors, the general question for us is: which classes of ozone monitors do we want to use as the source of the ambient ozone data that we will input to the dose-response functions to estimate the ozone damages to crop production? Obviously, we will want to use first whatever data are available from the *agricultural* monitors, because we are estimating damages to agriculture. However, there are agricultural monitors in only a few places; most agricultural areas do not have them. There are more than 3000 counties in the U.S., but in the lower 48 states (we exclude Alaska and Hawaii from our analysis), there are only 115 counties with agricultural monitors (Table 12-7). Ten of the lower 48 states do not have a single agricultural monitor. (In the 38 states with agricultural monitors, anywhere from 1 to 11 counties have agricultural monitors.) Fortunately, though, all of the twelve production regions that we consider do have agricultural monitors.

So, we will use data from the agricultural monitors, in the counties that have them. But how do we estimate ambient ozone levels in 1990 in the many agricultural counties that lack an agricultural monitor? We have two general choices. First, we could use as a proxy readings from the "next best" location/land-use class of monitor of Table 12-7 — say, rural/residential, or rural/forest. If a county did not have any of the next-best monitors, we would proceed to the third-best, and so on, down to the worst, which probably would be center-city/industrial. This hierarchical approach would take advantage of other available ozone data, but might not be accurate (the second-best, third-best, etc. monitors might be poor proxies for agricultural monitors), and in any case would be relatively complicated. We do not take this approach.

It is simpler and nearly as accurate to "fill in" the gaps with the data available from the agricultural monitors. We do this here. In any agricultural county that lacks ozone data from an agricultural monitor, we assume 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 (and 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[20].

We aggregate our ambient ozone observations at 7-hour and 12-hour seasonal averages in either parts per million or parts per hundred million, as dictated by the crop

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[19] We did not have information on land use for ozone monitors in 23 counties, and so excluded those monitors from our data set.

[20] A statistical interpolation technique called "kriging" has been used in previous studies to provide average, seasonal O_3 levels (see references and discussion in Lefohn and Altshuller, 1996: 4-43). With the kriging method, one estimates air quality at remote locations by interpolating between the available surrounding air-quality data, weighting the closest readings most heavily. Because this method weights the available surrounding air-quality readings, it might be more accurate than our use of the regional average as a proxy.

dose-response studies that we use to estimate agricultural damages. The 7-hour mean is the average ozone level from 9 am to 4 PM, while the 12-hour mean is for the period from 9 am to 9 PM. If more than three observations were missing during the 9 am to 4 PM period then we did not calculate either the 7-hour or the 12-hour mean for that day. If a county did not have an observation for any given day[21], then we used the state average for that day, and if the state did not have a reading we used the regional average for that day. (Recall that our model divides the lower forty-eight states into twelve production regions.) After calculating the mean for any given day we calculated the mean for the growing season, which we assume runs from May through September inclusive.

Initial (1990) ozone air quality (PI_{O3}) in simple yield-loss scaling model . In the simple yield-loss model, eq. 12-10, the dose-response (yield-loss) function Q is applied to national -- not county-level -- production of each crop. Hence, the air-quality parameter in the dose-response function (OZONE in eq. 12-11) 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-hour and 12-hour average ozone concentrations in rural areas of each state in the U. S. 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, as discussed above, 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, p. 4-43).

Given these estimates of average rural ozone air quality in each state, and data on the major producing states for each crop (see sources to Table 12-3), 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, but rather 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. Because we used our judgment, we estimated low and high values. The results are shown in Table 12-3.

12.4.7 Crop production data for the AOM8

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[21] In the 115 counties that have agricultural monitors with readings during the growing season, there are on average 141 days with valid ozone observations, with a range of between 48 and 153 days, out of the total 153 days of the growing season.

As discussed above, in the AOM8 we derive estimates of $QGAIN\%_{ir}$, for each of the 12 crop-production regions, from $QGAIN\%_{ic}$, which is estimated at the county level with county-level data on crop production. Crop production at the county level are reported every five years, most recently for 1987 (Bureau of the Census, 1987 Census of Agriculture, 1989). For the purpose of calculating regional QGAIN% from the county-level QGAIN%, 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 method assumes that from 1987 to 1990, production changed by the same factor — the national-average factor — in every county).

Recall that the simple yield-loss estimates of damages to crops other than the eight in the AOM8 (eq. 12-10) are based on the total reported value of crop production (Table 12-3), which is equal to the quantity produced multiplied by the producer price.

12.4.8 Updating to 1991$.

In this analysis, we use 1990 data on air quality, emissions, and crop production, but report our welfare estimates in 1991$ (because all estimates in the social-cost series are in 1991$). Thus, we must update the baseline prices in Howitt's model (the basis of the AOM8) from 1987 to 1991. To update the dollar results to 1991$, we multiplied the original calculated welfare results (in 1987$) by the ratio of the 1991 Producer Price Index (PPI) to the 1987 PPI. We did this separately for each of the eight crops, using the appropriate PPI. The Bureau of Labor Statistics (1988, 1992) lists PPIs specifically for alfalfa, barley, corn (we used the PPI for grain corn rather than fresh corn) cotton, soybeans, and wheat, but not for sorghum or rice. For these last two, we used the PPI for "other grains, not including wheat".

12.5 RESULTS OF THE ANALYSIS

12.5.1 Ozone damages to the eight major crops

Tables 12-8 and 12-9 show the welfare changes estimated by the AOM8 for the three emission-reduction scenarios, for the eight major crops. (These results in these two tables do not include effects on crops other than the eight shown in Table 12-6, or the effects of pollutants other than ozone.)

In all cases, the biggest change in producer surplus occurs in the Pacific-II region (Table 12-8). However, nearly all of the producer-surplus change in this region is due to a change in deficiency payments, which as discussed above 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 (Table 12-5), and the total value of soybean output is high (Table 12-3). Corn is not particularly 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 only; wheat is of moderate value, and only moderately sensitive to ozone.

Table 12-9 shows that anthropogenic ozone causes $3 to $5 billion in damages to the eight crops, and that ozone formed from motor-vehicle emissions causes $2 to $3 billion in damages to the eight crops (1991 dollars in 1990). Motor vehicles are responsible for such a large fraction of total damages because, in our model, most of the ozone precursor pollutants in agricultural areas come from motor vehicles.

Producers lose about three times as much as do consumers (compare CS with PS less DP), which implies that demand is relatively elastic and production functions relatively steep. Put another way, consumers can more readily make substitutions than can producers.

Note that in Table 12-9, 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 optimization model are nonlinear. 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 average cost is a reasonably proxy for any marginal cost.

12.5.2 Damages attributable to motor-vehicle use, including damage from pollutants other than ozone, and damages to crops other than the eight of Table 12-3.

Tables 12-10 and 12-11 show agricultural damages attributable to six different classes of motor-vehicles, including indirect emissions as well as direct emissions from vehicles themselves. The damage estimates in these tables, unlike the estimates in Tables 12-8 and 12-9, include ozone damages to crops other than the eight in the AOM8, and damages from pollutants other than ozone.

Gasoline vehicles cause much greater damages than do diesel vehicles, because they emit much more total VOC, 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%.

Again, note that the results for Case IIB are close to although not exactly equal to 10 times the results for Case IIA, which means that the average cost per mile or kg (Table 12-11) is an acceptable proxy for any marginal cost.

Table 12-11 shows costs per kg 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 $/kg results for each pollutant individually. Moreover, technically, the $/kg-[VOC+$NO_X$] results of Table 12-11 hold only for the actual proportions of VOCs and NO_X emitted in 1990. However, the results probably are reasonably accurate for up to moderate deviations from the 1990 proportions.

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.

12.5.3 Comparison of our results with those of other studies

Our results, shown in Table 12-9, are consistent with the estimates summarized from the literature in Table 12-1. We estimate that a 100% reduction in anthropogenic ozone would create benefits of $2.6 to $5.3 billion (1991$ 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) (Table 12-1), for reductions in total ambient ozone levels of 25% to 50%[22].

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[22] By "broadly consistent," we mean only 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, though, that for two reasons, it is not the case that with any particular model, the benefits of a 100% reduction in anthropogenic ozone will be *exactly* twice the benefits of a 50% reduction or four times the benefits of a 25% reduction in total ozone. First, the 100% is with respect to anthropogenic ozone , whereas the 50% and 25% are with respect to total ozone. (Anthropogenic ozone typically is on the order of 80% of total ozone). Second, damages are a nonlinear function of the change in ozone. Nevertheless, given that most ozone is anthropogenic, and that the damage function is not severely nonlinear, any particular model will estimate that the benefits of a 100% reduction in anthropogenic ozone are roughly twice the benefits of a 50% reduction or four times the benefits of a 25% reduction in total ozone.

Also, note that in our comparison of our results, we do not include our estimates of benefits to crops other than eight modeled here, or of benefits from reducing pollutants other than ozone.

12.5.4 Conclusion

We have used an agricultural optimization model (AOM8) 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 U.S., and eight major crops that account for some 63% of the total value of U.S. crop production. We find that motor-vehicle ozone damage to these eight crops amounts to $2 to $3 billion. Ozone damages to other crops, and damages to all crops from all other pollutants, probably are on the order of 80% of the ozone damages to the eight crops. Thus, pollution attributable to motor vehicle use probably causes $3 to $5 billion in agricultural damages, per year.

The estimated damages are much less than the damages to human health (Report #11 of this social-cost series), and thus probably constitute a relatively minor but not completely insignificant portion of the total cost of air pollution from motor vehicles.

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TABLE 12-1. SUMMARY OF RESULTS FROM LITERATURE REVIEW

Author (Year)	Pollutant (Crops)	Region (Year Analyzed)	P[a]	C[b]	I[c]	Annual Damages or Benefit of Control
Adams, Crocker, Thanavibulchai (1982)	Ambient oxidant exposure (14 crops)	Southern California, 4 production regions (1976)	Yes	Yes	Yes	$46 million benefit for a move from current levels to a situation without air pollution.
Brown and Smith (1984)	Ozone, (corn, wheat, soybeans)	Indiana, 9 production regions	Yes	Yes	No	No welfare calculations. Estimated substitution effects of ozone.
Mjelde, et al. (1984)	Ozone (corn, soybeans)	Illinois (1980)	No	Yes	Yes	$226 million loss in producer profits from a 10% increase in ozone. Consumer welfare not included.
Howitt, Gossard and Adams (1984)	Ozone (13 crops)	California, 14 production regions (1978)	Yes	Yes	Yes	$35.7 million benefit from reducing ozone to 0.04 ppm. $2.9 million loss from increasing ozone to 0.05 ppm. $157.3 million loss from increasing ozone to 0.08 ppm.
Adams, Hamilton, McCarl (1986)	Ozone (12 field crop and 5 livestock commodities)	U.S., 55 production regions (1980)	Yes	Yes	Yes	$1.7 billion benefit for a 25% reduction in ozone; $2.1 billion loss for a 25% increase in ozone.
Adams and McCarl (1985)	Ozone (corn, wheat, soybeans)	"Corn Belt," 5 states (1980)	Yes	Yes	Yes	$0.7 billion benefit from 25% reduction in ozone standard. Over $2 billion loss from increasing standard 25%.

TABLE 12-1, CONTINUED.

Energy Resources Consultants (1985)	Ozone and sulfur dioxide (33 crops)	San Joaquin Valley, California (1978)	Yes	Yes	Yes	Over $117 million loss due to pollution, 98% attributed to ozone.
Kopp, Vaughan, Hazilla and Carson (1985)	Ozone (corn, soybeans, wheat, cotton, peanuts)	U.S., 200 production regions (1978)	No	Yes	Yes	Over $1 billion benefit for reducing standard 25%. Almost $1.4 billion loss for increasing standard 25%.
Rowe and Chestnut (1985)	Ozone and sulfur dioxide (33 crops)	San Joaquin Valley (1978)	Yes	Yes	Yes	$42.6 million benefit from reducing ozone to 0.12 ppm; $105.9 million benefit from reducing ozone to 0.10 ppm; $117.4 million benefit from reducing ozone to 0.08 ppm.
Krupnick and Kopp (1988)	Ozone (barley, beans, corn, cotton, peanuts, sorghum, soybeans, tomatoes, wheat)	U.S. (1986)	Yes	Yes	Yes	$225 million benefit from a 10% ozone reduction; $538 million benefit from a 25% reduction; $1 billion benefit from a 50% reduction.
Adams, Glyer, Johnson and McCarl (1989)	Ozone (23 primary commodities, 12 secondary commodities)	U.S., 63 production regions (multi-year "base" period 1981-83)	Yes	Yes	Yes	$1.9 billion benefit (in 1982 dollars) from a 25% reduction in 1981-83 ozone levels.
Howitt and Goodman (1989)	Ozone (43 crops)	California, 17 production regions (1984)	Yes	Yes	Yes	$50 million benefit from reducing seasonal average to 0.06 ppm; $333 million benefit from reducing seasonal benefit to 0.025 ppm.

Notes to Table 12-1.

[a] Indicates whether or not price changes are endogenous in the analysis

[b] Indicates whether or not the analysis considers crop substitution as a response to ozone pollution

[c] Indicates whether or not the analysis considers input substitution as a response to ozone pollution.

TABLE 12-2. AGRICULTURAL PRODUCTION REGIONS IN THE AOM8

Regions	**States**
Northeast	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, W. Virginia, Kentucky, Tennessee, North Carolina
Southeast	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

Source: Howitt (1991b).

TABLE 12-3. PRODUCTION OF CROPS IN THE U. S.: VALUE (1990) AND OZONE EXPOSURE (1985/1986)

Crops	**Major Production States**	**Value**[a]	**Ave O_3 (ppm)**[b]	
	(in order of value of production)[a]	*($10^9 \$$)*	*low*	*high*
Eight crops in the AOM8				
Alfalfa Hay	Wisconsin, California, Iowa	6.6	0.040	0.046
Barley	North, Dakota, Montana, Idaho	0.9	0.040	0.044
Corn	Iowa, Illinois, Nebraska	18.2	0.038	0.044
Cotton	Texas, California, Mississippi	5.1	0.049	0.055
Rice	Arkansas, California, Louisiana	1.0	0.050	0.056
Grain Sorghum	Kansas, Texas, Nebraska	1.2	0.043	0.046
Soybean	Illinois, Iowa, Indiana	11.0	0.044	0.048
Wheat	Kansas, North Dakota, Montana	7.2	0.041	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[c]	1.7	0.053	0.056
Tomatoes	California, Florida[d]	1.6	0.051	0.057
Oranges	Florida, California	1.5	0.042	0.046
Apples	Washington, New York, California[e]	1.4	0.040	0.048
Sugarbeets	Minnesota, Idaho, California	1.2	0.044	0.048
Peanuts	Georgia, Texas, North Carolina[f]	1.2	0.048	0.052
Lettuce	California[g], Arizona	1.1[h]	0.058	0.062
Sugarcane	Florida, Hawaii, Louisiana	0.9	0.042	0.045
Subtotal 10 crops	--	*15.8*	--	--
All other crops	California, Florida[i]	*13.8*	0.044	0.050
All crops	all (entire U. S.)	*80.8*	--	--

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[a] From the National Agricultural Statistics Service (NASS) (1995a-d), except as noted. Value is value of production.

[b] This is the (roughly) production-weighted national-average “kriged” rural ozone air quality for each crop, in 1985/1986. See section 12.4.6. Note that this is the air quality estimated for the purpose of scaling the AOM8 results to account for damages to crops not in the AOM8; *not* the air quality estimated for use in the AOM8.

[c] Over 90% of the value is in California.

[d] Florida is the leading producer of tomatoes for the fresh market, but California is virtually the sole producer of tomatoes for processing.

[e] Washington is by far the largest producer. After 1990, California overtook New York.

[f] Ranking of producing states based on production of peanuts for nuts. In every year from 1987 to 1992 except 1990, Alabama produced more nuts than did North Carolina.

[g] California is by far the leading producer.

[h] In 1990, the value of head lettuce production was $0.84 billion. The value of production of leaf lettuce and romaine lettuce was not reported until 1992. On the basis of the 1992 total-lettuce/head-lettuce ratios, we estimate that the total lettuce production in 1990 was worth $1.1 billion.

[i] Our assumption, based on the total value of production of all fruits and nuts and vegetables (NASS, 1995a-d). California alone accounts for more than half of the total value; Florida, for another 10%-15%.

TABLE 12-4. YIELD-RESPONSE FUNCTIONS

Crop[a]	Equation[a]	High/Low[b]	Source
Eight crops in the AOM8			
Alfalfa Hay	$32.67-139.02*12h$	high	Olszyk et al. (1986)
	$\exp-(12h/0.187)^{1.57}$	low	Temple et al. (1986)
Barley	$\exp-(7h/0.205)^{4.278}$	low = high	Heck et al. (1984)
Corn	$314.98-841.52*12h$	high	Thompson et al. (1976)
	$\exp-(7h/0.160)^{4.284}$	low	Heck et al. (1984)
Cotton	$\exp-(7h/0.088)^{2.1}$	high	Heck et al. (1984)
	$\exp-(7h/0.111)^{2.71}$	low	Heagle et al. (1979)
Rice	$\exp-(7h/0.2016)^{2.474}$	low = high	Kats and Dawson (1985)
Sorghum	$\exp-(7h/0.296)^{2.217}$	high	Heck et al. (1984)
	$\exp-(7h/0.317)^{2.952}$	low	Kress, et al. (1985)
Soybean	$\exp-(7h/0.128)^{0.872}$	low = high	Heck et al. (1984)
Wheat	$\exp-(7h/0.143)^{2.423}$	low = high	Heck et al. (1984)
Ten most valuable crops not in the AOM8			
Tobacco	$\exp-(12h/0.145)^{1.66}$	low = high	Lesser et al. (1990)
Potatoes	$\exp-(7h/0.204)^{1.67}$	high	assume dry beans[c]
	$\exp-(7h/0.204)^{1.67}$	low	assume tomatoes[d]
Grapes	$11.21-66*12h$	low = high	Olszyk et al. (1988)[e]
Tomatoes	$\exp-(7h/0.204)^{1.67}$	low = high	Lesser et al. (1990)
Oranges	$33.452-172.6*12h$	low = high	Olszyk et al. (1988)
Apples	$32.67-139.02*12h$	high	assume alfalfa[f]
	$\exp-(7h/0.204)^{1.67}$	low	assume tomatoes[f]
Sugarbeets	$\exp-(7h/0.093)^{2.70}$	high	assume turnips[g]
	0 (no response)	low	Olszyk et al. (1988)
Peanuts	$\exp-(7h/0.109)^{2.27}$	low = high	Lesser et al. (1990)
Lettuce	$1065.7-5978*7h$	high	Heck et al. (1982)[j]
	$\exp-(7h/0.120)^{9.76}$	low	Lesser et al. (1990)[j]
Sugarcane	$\exp-(7h/0.093)^{2.70}$	high	assume sugarbeets
	0 (no response)	low	assume sugarbeets
All others	$\exp-(12h/0.139)^{1.95}$	high	assume forage[i]
	$\exp-(12h/0.178)^{2.07}$	low	assume alfalfa[i]

All of the dose-response equations except perhaps that for grapes are derived from experiments with open-top chambers. Note that in the Weibull (exponential) functions (eq. 12-11), we do not show the coefficient μ, because it drops out in the calculation of QGAIN%. Appendix A discusses the results of some of the studies which generated the functions, and compares the ozone sensitivity of the crops not in the AOM8 with the sensitivity of the crops in the AOM8.

[a] *7h* refers to the 7 hour mean ozone concentration in parts per million between 9:00 am to 4:00 PM. *12h* refers to the 12 hour mean ozone concentration in parts per million between 9:00 am to 9:00 PM.

[b] "High" identifies the equation that generated the higher response estimate, and "low" the equation that generated the lower estimate.

[c] Energy and Resource Consultants (1985) indicate that potatoes are about as sensitive to ozone as are dry beans. Therefore, in our high-cost case, we use the Olszyk et al. (1988) function for dry beans, which results in relatively large yield losses.

[d] Howitt et al. (1984) use the relative yield sensitivity of tomatoes as a surrogate for the sensitivity of potatoes.

[e] Olszyk et al. (1988) actually show the function as $1.121-66*12h$, but this gives nonsensical results, whereas 11.21 (instead of 1.121) reproduces the yield-loss results that they report. It appears, then, that there is a decimal typographical error in the publication.

[f] Energy and Resource Consultants (1985) state that crab apples are sensitive to ozone, but that "delicious" apples are tolerant. This suggests to us that all apples are only moderately sensitive to ozone. The use of the tomato and alfalfa functions reflects this reasonably well.

[g] Our assumption. We use the NCLAN function for turnips (Lesser et al., 1990).

[h] These two functions, both from the NCLAN experiments, give vastly different results: the Weibull function of Lesser et al. (1990) results in essentially no yield loss, whereas the linear function of Heck et al. (1982) results in an extremely large yield loss. It is possible that the function reported by Lesser et al. (1990) is meant to supersede the function reported by Heck et al. (1982); however, the shape exponent (9.76) in the Lesser et al. (1990) function has a relatively large standard error, which according to Lesser et al. (1990) "arose primarily because the chosen levels of O_3 for the studies were not sufficiently high to provide an adequate definition of the Weibull response" (p. 153). For this reason, we retain the earlier NCLAN function as an alternative, in our high-cost case.

Olszyk et al. (1988) report a function similar to the NCLAN Weibull function of Lesser et al. (1990): $\exp-(7h/0.122)^{8.837}$. Energy and Resource Consultants (1985) use the linear function of Heck et al. (1982) in their assessment of crop loss in California.

[i] In our low-cost case, we assume the final NCLAN dose-response function for alfalfa (Lesser et al., 1990), a somewhat tolerant crop. In our high-cost case, we assume the final NCLAN dose-response function for forage (Lesser et al., 1990), a somewhat sensitive crop.

Table 12-5. Estimated yield responses to ozone (QGAIN%, Case I) of the eight major crops in the twelve production regions (percentage change)

	Alfalfa Hay		**Barley**		**Corn**		**Cotton**	
Regions	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
Northeast	6.5	12.3	0.2	0.2	0.5	7.5	0.0	0.0
Lake States	4.7	9.5	0.1	0.1	0.3	6.0	0.0	0.0
Corn Belt	5.6	11.1	0.1	0.1	0.4	6.8	2.9	8.6
Appalachian	5.8	10.4	0.2	0.3	0.7	5.5	7.6	19.7
Southeast	4.5	7.7	0.2	0.2	0.7	4.2	7.2	18.4
Delta States	2.5	4.6	0.0	0.0	0.4	3.6	5.3	14.6
South. Plains	5.2	9.9	0.1	0.1	0.5	6.6	7.4	22.1
North. Plains	3.9	7.9	0.1	0.1	0.2	4.6	0.0	0.0
Mountain-I	2.6	4.8	0.1	0.1	0.4	4.5	0.0	0.0
Mountain-II	4.5	8.0	0.2	0.2	0.5	3.9	9.1	24.9
Pacific-I	1.4	3.2	0.0	0.0	0.1	2.3	0.0	0.0
Pacific-II	7.4	13.3	0.3	0.3	0.6	6.1	15.4	39.7

	Rice		**Sorghum**		**Soybean**		**Wheat**	
Regions	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
Northeast	0.0	0.0	0.3	1.4	19.6	23.9	5.5	6.0
Lake States	0.0	0.0	0.0	0.0	14.3	18.0	2.6	3.1
Corn Belt	0.8	0.9	0.2	0.8	17.3	21.4	4.2	4.7
Appalachian	0.4	0.5	0.3	1.2	13.0	15.8	5.2	5.9
Southeast	3.1	3.4	0.3	1.1	10.6	13.0	4.7	5.4
Delta States	1.4	1.7	0.2	0.9	9.0	11.2	3.5	4.1
South. Plains	2.0	2.3	0.3	1.3	13.2	16.6	4.9	5.5
North. Plains	0.0	0.0	0.2	0.8	11.9	15.3	2.9	3.4
Mountain-I	0.0	0.0	0.2	0.8	10.5	12.8	3.0	3.5
Mountain-II	0.0	0.0	0.3	1.2	12.3	15.4	5.0	5.7
Pacific-I	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.4
Pacific-II	1.8	2.0	0.3	1.3	0.0	0.0	6.3	7.0

Notes to Table 12-5:

The percentages shown are the calculated “QGAIN%” values for each region, where, as explained in the text, “QGAIN%” is the percentage yield loss due to ozone being at its actual 1990 levels rather than at natural background levels. See the text and eq. 12-13 for details.

We derived the "low" and the "high" costs in this table as follows. First, we specified the set of parameter values that resulted in the smallest total welfare gain in case II, in which we eliminate motor-vehicle emissions. Then, we specified the set of parameter values that resulted in the greatest total welfare gain in case II. We thus got two sets of parameter values, one giving the low gain and one giving the high gain for case II. Then, with these same two sets of parameter values, we ran case I, in which we eliminate all anthropogenic pollution. For each crop and region, we got two results for QGAIN% for case I — one result for each set of parameter values from case II. For each crop and region in this table, the "low" value is the lower of the two results corresponding to the two sets of parameter values, and the "high" value is the other. (Ideally, we would have defined the "low" and the "high" here to have generated the low and high welfare changes in case I.)

TABLE 12-6. PRICE ELASTICITIES OF DEMAND

Crop	Price Elasticity
Alfalfa Hay	-0.10
Barley	-0.55
Corn	-0.32
Cotton	-0.20
Grain Sorghum	-0.05
Rice	-0.73
Soybean	-0.25
Wheat	-0.48

Source: model documented in Howitt (1991b).

TABLE 12-7. NUMBER OF COUNTIES WITH OZONE MONITORS, BY GENERAL LOCATION AND LAND-USE CLASSIFICATION

Land Use	**General Location**[a]			*Land Use Subtotal*[a]
	Urban and Center City	Suburban	Rural	
Residential	50	161	44	*224*
Commercial	64	71	10	*133*
Industrial	12	25	16	*49*
Agricultural	0	2	112	*115*
Forest	0	2	39	*40*
Desert	0	1	9	*10*
Mobile	6	9	1	*16*
Blighted area	0	0	0	*0*
Location Subtotal[a]	*114*	*229*	*215*	*442*

Each cell entry is the number of counties (not the number of monitors) for which we have ozone data from the location-and-land-use type of monitor defined by the cell.

[a] The row or column subtotals are not necessarily equal to the sum of the of the cell values in each row or column because: 1) there is overlap between categories (i.e., the same county may appear in more than one of the cells, which will cause the subtotal to be lower); and 2) in three counties there are monitors with land-use information but without general-location information, so they will *not* appear in the individual cells, but *will* appear in the subtotal.

TABLE 12-8A. CHANGE IN PRODUCER SURPLUS AND DEFICIENCY PAYMENTS DUE TO OZONE AIR POLLUTION IN THE MARKETS FOR EIGHT MAJOR CROPS, CASE I: ELIMINATE ANTHROPOGENIC OZONE-PRECURSOR EMISSIONS (BILLIONS OF 1991 DOLLARS)

	Change in PS[a]		Change in DP[b]	
Region	*Low*	*High*	*Low*	*High*
Northeast	0.118	0.256	-0.002	0.021
Lake States	0.192	0.466	-0.013	0.084
Corn Belt	0.700	1.606	-0.067	0.432
Appalachian	0.177	0.340	-0.001	0.035
Southeast	0.090	0.176	0.008	0.039
Delta States	0.344	0.923	0.184	0.579
Southern Plains	0.469	1.302	0.341	0.947
Northern Plains	0.106	0.262	0.023	0.105
Mountain-I	0.052	0.094	0.016	0.016
Mountain-II	0.051	0.144	0.012	0.036
Pacific-I	0.009	0.021	0.002	0.002
Pacific-II	2.057	5.608	1.810	4.978
Total	**4.366**	**11.198**	**2.312**	**7.276**

Case I is a 100% reduction in anthropogenic emissions of VOCs and NOx.

These are the AOM8 estimates of the effect of ozone air pollution on the eight major crops shown in Table 12-6. The results shown in this table do *not* include ozone effects on crops other than the eight, or the effects of pollutants other than ozone.

[a] PS = producer surplus. Calculated using eq. 12-2a and 12-2b. Includes deficiency payments. See the text for details.

[b] DP = deficiency payments. Calculated using eq. 12-4a. See the text for details.

TABLE 12-8B. CHANGE IN PRODUCER SURPLUS AND DEFICIENCY PAYMENTS DUE TO OZONE AIR POLLUTION IN THE MARKETS FOR EIGHT MAJOR CROPS, CASE IIA: ELIMINATE 10% OF MOTOR-VEHICLE-RELATED OZONE-PRECURSOR EMISSIONS (BILLIONS OF 1991 DOLLARS)

	Direct Emissions Only[a]				**Direct + Indirect**[b]			
	Change in PS[c]		Change in DP[d]		Change in PS[c]		Change in DP[d]	
Region	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
Northeast	0.008	0.014	0.000	0.001	0.008	0.015	0.000	0.001
Lake States	0.014	0.026	-0.001	0.005	0.015	0.028	-0.001	0.005
Corn Belt	0.045	0.087	-0.003	0.024	0.052	0.095	-0.003	0.027
Appalachian	0.010	0.016	0.000	0.002	0.010	0.016	0.000	0.002
Southeast	0.005	0.008	0.001	0.002	0.005	0.008	0.001	0.002
Delta States	0.020	0.045	0.012	0.029	0.021	0.047	0.012	0.030
Southern Plains	0.035	0.069	0.025	0.049	0.044	0.079	0.032	0.056
Northern Plains	0.007	0.012	0.002	0.005	0.009	0.014	0.002	0.006
Mountain-I	0.003	0.004	0.001	0.001	0.003	0.005	0.001	0.001
Mountain-II	0.004	0.008	0.001	0.002	0.004	0.009	0.001	0.002
Pacific-I	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000
Pacific-II	0.101	0.247	0.089	0.219	0.120	0.255	0.106	0.227
Total	**0.251**	**0.538**	**0.129**	**0.341**	**0.291**	**0.571**	**0.152**	**0.360**

Case IIA is a 10% reduction in motor-vehicle related emissions of VOCs and NOx. These are the AOM8 estimates of the effect of ozone air pollution on the eight major crops shown in Table 12-6. The results shown in this table do *not* include ozone 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.

[b] 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, and so on. See Report #10 for details.

[c] PS = producer surplus. Calculated using eq. 12-2a and 12-2b. Includes deficiency payments. See the text for details.

[d] DP = deficiency payments. Calculated using eq. 12-4a. See the text for details.

TABLE 12-8C. CHANGE IN PRODUCER SURPLUS AND DEFICIENCY PAYMENTS DUE TO OZONE AIR POLLUTION IN THE MARKETS FOR EIGHT MAJOR CROPS, CASE IIB: ELIMINATE 100 % OF MOTOR-VEHICLE-RELATED OZONE-PRECURSOR EMISSIONS (BILLIONS OF 1991 DOLLARS)

	Direct Emissions Only[a]				**Direct + Indirect[b]**			
	Change in PS[c]		Change in DP[d]		Change in PS[c]		Change in DP[d]	
Region	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
Northeast	0.083	0.175	-0.001	0.014	0.087	0.179	-0.001	0.015
Lake States	0.151	0.295	-0.009	0.055	0.162	0.308	-0.010	0.057
Corn Belt	0.461	0.914	-0.039	0.247	0.525	0.999	-0.046	0.269
Appalachian	0.109	0.193	0.001	0.020	0.112	0.197	0.001	0.020
Southeast	0.051	0.099	0.006	0.022	0.051	0.099	0.007	0.022
Delta States	0.208	0.502	0.115	0.316	0.215	0.512	0.121	0.324
Southern Plains	0.324	0.655	0.234	0.476	0.391	0.740	0.282	0.535
Northern Plains	0.075	0.118	0.017	0.050	0.092	0.136	0.019	0.056
Mountain-I	0.034	0.050	0.012	0.010	0.037	0.051	0.013	0.011
Mountain-II	0.034	0.088	0.008	0.023	0.037	0.091	0.009	0.024
Pacific-I	0.006	0.012	0.002	0.001	0.006	0.012	0.002	0.001
Pacific-II	1.003	2.704	0.886	2.399	1.162	2.786	1.028	2.473
Total	**2.540**	**5.804**	**1.233**	**3.633**	**2.876**	**6.111**	**1.423**	**3.808**

Case IIB is a 100% reduction in motor-vehicle related emissions of VOCs and NOx.

These are the AOM8 estimates of the effect of ozone air pollution on the eight major crops shown in Table 12-6. The results shown in this table do *not* include ozone effects on crops other than the eight, or the effects of pollutants other than ozone.

[a,b,c,d] See notes to Table 12-8b.

TABLE 12-9. TOTAL CHANGE IN PRODUCER SURPLUS, CONSUMER SURPLUS, DEFICIENCY PAYMENTS, AND TOTAL WELFARE, DUE TO OZONE AIR POLLUTION, IN THE MARKETS FOR EIGHT MAJOR CROPS IN ALL REGIONS (BILLIONS OF 1991 DOLLARS)

	Case I		**Case IIA**				**Case IIB**			
			Direct emissions[a]		**Direct + Indirect**[b]		**Direct emissions**[a]		**Direct + Indirect**[b]	
	Low	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
Change in PS[c]	4.37	11.20	0.25	0.54	0.29	0.57	2.54	5.80	2.88	6.11
Change in DP[c]	2.31	7.28	0.13	0.34	0.15	0.36	1.23	3.63	1.42	3.81
Change in CS[d]	0.58	1.42	0.03	0.07	0.04	0.07	0.36	0.74	0.41	0.80
Change in welfare[e]	**2.63**	**5.34**	**0.16**	**0.26**	**0.18**	**0.28**	**1.67**	**2.91**	**1.86**	**3.10**

Case I is a 100% reduction in anthropogenic emissions of VOCs and NOx. Case IIA is a 10% reduction in motor-vehicle related emissions of VOCs and NOx. Case IIB is a 100% reduction in motor-vehicle related emissions of VOCs and NOx.

These are the AOM8 estimates of the effect of ozone air pollution on the eight major crops shown in Table 12-6. The results shown in this table do *not* include ozone effects on crops other than those in the AOM8, or the effects of pollutants other than ozone.

[a,b] See notes to Table 12-8b.

[c] From Table 12-8.

[d] CS = consumer surplus. Calculated using eq. 12-3a and 12-3b. See the text for details. Because we have national, but not regional demand functions, we cannot calculate consumer surplus regionally.

[e] Equal to ΔPS plus Δ CS minus Δ DP.

TABLE 12-10. THE CHANGE IN WELFARE IN ALL CROP MARKETS DUE TO A REDUCTION IN MOTOR-VEHICLE RELATED EMISSIONS (BILLIONS OF 1991 DOLLARS) [a]

	Direct emissions[b]		**Direct + Indirect[c]**	
Case IIA: 10% reduction in emissions[d]	*Low*	*High*	*Low*	*High*
LDGAs	0.15	0.28	0.18	0.30
LDGTs	0.07	0.12	0.07	0.13
HDGVs	0.01	0.02	0.01	0.02
All gasoline vehicles	*0.23*	*0.41*	*0.26*	*0.44*
LDDAs	0.00	0.00	0.00	0.02
LDDTs	0.00	0.00	0.00	0.00
HDDVs	0.04	0.08	0.05	0.08
All diesel vehicles	*0.05*	*0.08*	*0.05*	*0.08*
All gasoline and diesel vehicles	*0.28*	*0.49*	*0.31*	*0.53*
Case IIB: 100% reduction in emissions[e]	**2.95**	**5.39**	**3.28**	**5.75**

LDGA = light-duty gasoline auto; LDGT = light-duty gasoline truck; HDGV = heavy-duty gasoline vehicle; LDDA = light-duty diesel auto; LDDT = light-duty diesel truck; HDDV = heavy-duty diesel vehicle.

These results *do* include ozone effects on crops other than those in the AOM8, and the effects of pollutants other than ozone (see eq. 12-10).

[a] Equal to change in consumer surplus plus change in producer surplus minus change in deficiency payments.

[b] Direct emissions are tailpipe and evaporative emissions from motor vehicles.

[c] 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, and so on. See Report #10 for details.

[d] Case IIA is a 10% reduction in emissions of VOCs and NOx.

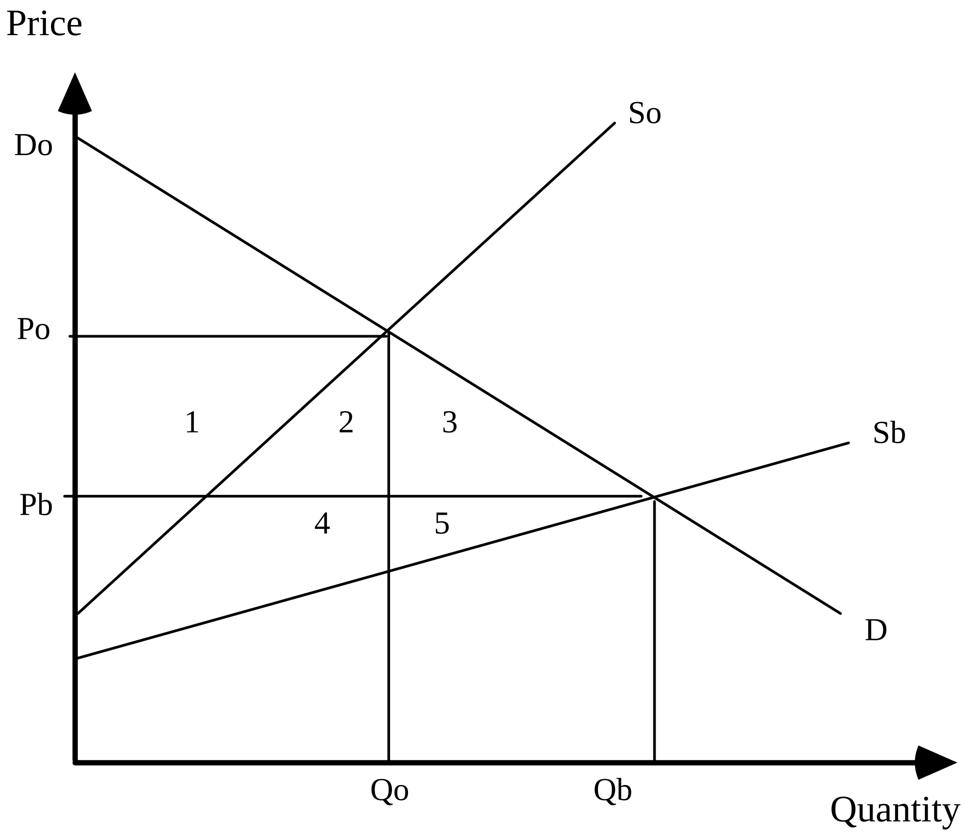
[e] Case IIB is a 100% reduction in emissions of VOCs and NOx.

TABLE 12-11. THE CHANGE IN WELFARE IN ALL CROP MARKETS DUE TO A 10% REDUCTION IN MOTOR-VEHICLE RELATED EMISSIONS (1991$/1000-VMT, AND 1991$/KG-[NO_X+VOCS])

	$/1000-VMT				**$/kg-[VOCs+$NO_X$]**			
	Direct emissions		**Direct + Indirect**		**Direct emissions**		**Direct + Indirect**	
Case IIA: 10% reduction	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
LDGAs	0.99	1.77	1.13	1.91	0.19	0.29	0.17	0.26
LDGTs	1.67	2.97	1.91	3.21	0.20	0.31	0.18	0.27
HDGVs	3.99	6.56	4.57	7.18	0.14	0.23	0.13	0.21
All gasoline vehicles	*1.16*	*2.08*	*1.33*	*2.24*	*0.19*	*0.29*	*0.17*	*0.26*
LDDAs	0.37	0.57	0.40	7.44	0.21	0.33	0.19	3.47
LDDTs	0.13	0.22	0.20	0.28	0.21	0.33	0.14	0.20
HDDVs	3.40	5.74	3.69	6.02	0.19	0.32	0.17	0.28
All diesel vehicles	*2.69*	*4.53*	*2.93*	*4.76*	*0.19*	*0.32*	*0.17*	*0.28*
All gasoline, diesel vehicles	*1.29*	*2.28*	*1.46*	*2.45*	*0.19*	*0.30*	*0.17*	*0.26*
Case IIB: 100% reduction	**1.37**	**2.51**	**1.53**	**2.68**	**0.20**	**0.33**	**0.18**	**0.29**

See the notes to Table 12-10. VMT = vehicle-miles of travel. These values are calculated by dividing the $ results of Table 12-10 by 1000s of miles in each vehicle class, or by the sum of VOC and NO_X from each vehicle class and associated indirect emission sources. Thus, we effectively "assign" all damages, including damages from pollutants other than ozone, to the sum of VOC + NO_X emissions. To the extent that other emitted pollutants, such as CO or SO_X, are responsible for some of the damaging ambient pollution, we will overestimate the actual $/ton cost of VOC + NO_X emissions.

FIGURE 12-1. CHANGES IN PRODUCER AND CONSUMER SURPLUS DUE TO A REDUCTION IN OZONE CONCENTRATIONS

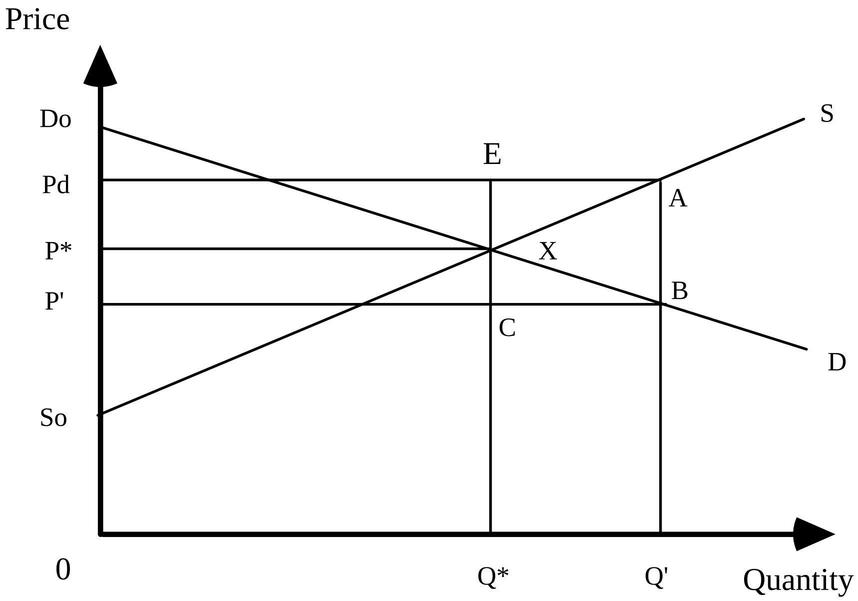


See section 12.2 for discussion.

The superscript *o* refers to current (1990) ozone levels, and the superscript *b* refers to background ozone level or the level without motor-vehicle related pollution.

This diagram is for illustrative purposes only. The difference between Sb and So has been exaggerated, and no inferences should be made about the relative sizes of the various regions shown in this diagram.

FIGURE 12-2. ANALYSIS OF THE WELFARE IMPACTS DUE TO DEFICIENCY PAYMENTS



APPENDIX A: RESULTS OF YIELD-LOSS STUDIES

Olszyk et al. (1988) used data on crop production and ozone air quality in each county in California in 1984, and yield loss-equations for 20 crops, to estimate the reduction in yield due to the difference between actual ozone levels and a presumed "background" level of 0.025 ppm (12-hr) or 0.027 ppm (7-hr). Winer et al. (1990?) do essentially the same thing, for 1986[23]. Their estimates show the combined effect of ozone exposure and crop sensitivity, holding producer behavior constant:

	% loss vs. 0.025 ppm	
Crop	*1984*	*1986*
Alfalfa hay	8.9	10.6
Barley (all types)	0	0
Beans (dry)	23.5	20.9
Corn (all types)	1.5-6.1	1.7-2.0
Cotton	18.8	15.7
Sorghum for grain	0	1.0
Grapes (all types)	22.4	22.5-26.5
Honeydew melons	n.r.	21.3
Lemons	20.4	9.4
Lettuce	0	0
Onions (all types)	24.4	0.9-1.0
Oranges	19.8	9.3
Rice	2.2	2.5
Spinach	3.5	0.4
Strawberries	0	0
Sugar Beets	0	0
Tomatoes (all types)	2.9-4.2	1.6-2.4
Watermelons	n.r.	35.6
Wheat (all types)	0.8	0.8

The Winer et al. (1990?) estimates for 1986 are consistent with the Olszyk et al. (1988) estimates for 1984, except that Winer et al. (1990?) estimate no effect on onions, and smaller effects on citrus fruits. Both sets of estimates of the yield loss for the 8 crops that are in AOM8 are broadly consistent with our estimates, based on other sources, of the loss for those eight crops in 1990 (Table 12-5).

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[23] It appears that Winer et al. (1990?) use many of the same dose-response functions that Olszyk et al. (1988) used. CARB (1987) also uses many of the same functions used in Olszyk et al. (1988), and reports similar yield-loss results.

The results of Olszyk et al. (1988) and Winer et al. (1990?) suggest that in California, the largest agricultural producer in the nation, crops other than the eight included in the AOM8 are at least as sensitive to ozone as are the eight included crops. For example, grapes, beans, melons, and citrus fruits, which are not included in the AOM8, all suffered considerably greater percentage yield losses than did five of the eight crops included in the AOM8: barley, corn, rice, sorghum, and wheat.

Other experiments have produced similar results. Heck et al. (1982) fit linear ozone/yield functions to results from some of the initial NCLAN open-top chamber experiments[24], and found that the functions predicted relatively large percentage yield reductions for turnips, spinach, peanuts, lettuce, and soybeans, moderate reductions for wheat and kidney beans, and a small reduction for corn (for ozone at 0.06 or 0.10 ppm vs. a presumed background of 0.025 ppm.)

Lesser et al. (1990) present the nonlinear Weibull response equations derived from the experimental results of the 1980-1987 NCLAN chamber studies of the ozone response of 14 crops at 41 sites across the country. Their summary of the percentage yield losses at three ozone levels (0.04, 0.05, and 0.06 ppm), relative to a background level of 0.025 ppm, is similar to the results shown above from the California study of Olszyk et al. (1988), and to the early NCLAN results summarized by Heck et al. (1982): alfalfa, corn, barley, sorghum, tomatoes, and lettuce are markedly less sensitive to ozone than are cotton, soybeans, peanuts, tobacco, and turnips. The results for wheat and beans were mixed.

Energy and Resource Consultants (1985) provide the following ranking from most to least sensitive to ozone.

Beans (dry)
Potatoes
Cotton
Lettuce
Grapes
Alfalfa
Tomatoes
Oranges
Peaches
Almonds

Summary. There are some inconsistencies in the yield losses in the studies cited above -- for example, as regards lettuce, spinach, beans, and onions -- but generally the picture is clear: among the eight crops included in the agricultural production model used in this analysis, only soybeans are quite sensitive to ozone, with cotton and perhaps alfalfa being moderately sensitive, whereas several of the major crops not

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[24] A few of the yield-response functions in Olszyk et al. (1988) are from later work by Heck et al.

included in this analysis appear to be at least moderately sensitive: tobacco, grapes, peanuts, citrus fruits, melons, and potatoes at least.