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### Publication Date

1996-04-01

# **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*

**UCD-ITS-RR-96-3 (12)**

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April 1996

## ACKNOWLEDGMENTS

This report is one in a series that documents an analysis of the full social-cost of motor-vehicle use in the United States. The series is entitled *The Annualized Social Cost of Motor-Vehicle Use in the United States, based on 1990-1991 Data*. Support for the social-cost analysis was provided by Pew Charitable Trusts, the Federal Highway Administration (through Battelle Columbus Laboratory), the University of California Transportation Center, the University of California Energy Research Group (now the University of California Energy Institute), and the U. S. Congress Office of Technology Assessment.

Many people provided helpful comments and ideas. In particular, we thank David Greene, Gloria Helfand, Arthur Jacoby, Bob Johnston, Charles Komanoff, Alan Krupnick, Charles Lave, Douglass Lee, Steve Lockwood, Paul McCarthy, Peter Miller, Steve Plotkin, Jonathan Rubin, Ken Small, Brandt Stevens, Jim Sweeney, Todd Litman, and Quanlu Wang for reviewing or discussing parts of the series, although not necessarily this particular report. Of course, we alone are responsible for the contents of this report.







# TABLE OF CONTENTS

ACKNOWLEDGMENTS .....	i
REPORTS IN THE SERIES .....	ii
LIST OF ACRONYMS .....	iii
TABLE OF CONTENTS.....	v
12. THE COST OF CROP DAMAGE CAUSED BY OZONE AIR POLLUTION FROM MOTOR VEHICLES.....	1
12.1 INTRODUCTION.....	1
12.2 THEORETICAL DISCUSSION.....	1
12.2. Changes in producer and consumer surplus due to a reduction in ambient ozone concentrations .....	1
12.2.2 The effects of a crop price subsidy on social welfare .....	2
12.3 LITERATURE REVIEW .....	4
12.3.1 Introduction .....	4
12.3.2 Reviews (see Table 12-1).....	5
12.4 THE MODEL.....	8
12.4.1 Overview .....	8
12.4.2 The welfare effects of changes in agricultural production.....	10
12.4.3 The objective function and the equilibrium quantities of inputs $X_{jir}$ .....	12
12.4.4 Dose-response functions .....	18
12.4.5 Air-quality modeling and data.....	21
12.4.6 Crop production data .....	26
12.4.7 Updating to 1991\$. .....	26
12.5 RESULTS OF THE ANALYSIS .....	27
12.5.1 Ozone damages to the eight major crops.....	27
12.5.2 Accounting for damages to other crops, and damages from other pollutants.....	28
12.5.3 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. ....	29
12.5.4 Comparison of our results with those of other studies .....	30
12.5.5 Conclusion.....	30
12.7 REFERENCES.....	31



## TABLES

TABLE 12-1. SUMMARY OF RESULTS FROM LITERATURE REVIEW .....	37
TABLE 12-2. AGRICULTURAL PRODUCTION REGIONS.....	40
TABLE 12-3. 1990 VALUE OF PRODUCTION FOR THE EIGHT MAJOR CROPS INCLUDED IN THE ANALYSIS (BILLIONS OF 1990 DOLLARS).....	41
TABLE 12-4. DOSE-RESPONSE FUNCTIONS.....	42
TABLE 12-5. ESTIMATED YIELD RESPONSES (QGAIN%, CASE I) OF THE EIGHT MAJOR CROPS IN THE TWELVE PRODUCTION REGIONS (PERCENTAGE CHANGE) .....	43
TABLE 12-6. PRICE ELASTICITIES OF DEMAND.....	45
TABLE 12-7. NUMBER OF COUNTIES WITH OZONE MONITORS, BY GENERAL LOCATION AND LAND-USE CLASSIFICATION .....	46
TABLE 12-8A. CHANGE IN PRODUCER SURPLUS AND DEFICIENCY PAYMENTS, CASE I: ELIMINATE ANTHROPOGENIC OZONE-PRECURSOR EMISSIONS (BILLIONS OF 1991 DOLLARS).....	47
TABLE 12-8B. CHANGE IN PRODUCER SURPLUS AND DEFICIENCY PAYMENTS, CASE IIA: ELIMINATE 10% OF MOTOR-VEHICLE-RELATED OZONE- PRECURSOR EMISSIONS (BILLIONS OF 1991 DOLLARS).....	48
TABLE 12-8C. CHANGE IN PRODUCER SURPLUS AND DEFICIENCY PAYMENTS, CASE IIB: ELIMINATE 100 % OF MOTOR-VEHICLE-RELATED OZONE-PRECURSOR EMISSIONS (BILLIONS OF 1991 DOLLARS) .....	49
TABLE 12-9. TOTAL CHANGE IN PRODUCER SURPLUS, CONSUMER SURPLUS, DEFICIENCY PAYMENTS, AND TOTAL WELFARE IN ALL REGIONS (BILLIONS OF 1991 DOLLARS) .....	50
TABLE 12-10. THE CHANGE IN WELFARE DUE TO A REDUCTION IN MOTOR- VEHICLE RELATED EMISSIONS (BILLIONS OF 1991 DOLLARS) A .....	51
TABLE 12-11. THE CHANGE IN WELFARE DUE TO A 10% REDUCTION IN MOTOR-VEHICLE RELATED EMISSIONS (1991\$/1000-VMT, AND 1991\$/KG-[NO <sub>x</sub> +VOCs]) .....	52

## FIGURES

FIGURE 12-1. CHANGES IN PRODUCER AND CONSUMER SURPLUS DUE TO A REDUCTION IN OZONE CONCENTRATIONS.....	53
FIGURE 12-2. ANALYSIS OF THE WELFARE IMPACTS DUE TO DEFICIENCY PAYMENTS.....	54

## 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 suggests that ozone, either alone or in combination with nitrogen dioxide and sulfur dioxide, may be responsible for up to 90 percent of U.S. crop losses resulting from air pollution (Heck et al., 1982). In an effort to address this problem, the Clean Air Act and its amendments include air pollution damages to vegetation as one of the criteria by which secondary national ambient air quality standards are evaluated (Adams et al., 1984).

There is, of course, an economic cost associated with this reduced productivity. In this paper we use a formal model of agricultural production and demand to estimate the cost of crop damage<sup>1</sup> due to all anthropogenic ozone air pollution, and to ozone air pollution attributable to motor-vehicle use in the U. S. in 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 curve shifts out 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  $Q^b$ .

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<sup>1</sup>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.

Society gains in economic welfare as a result of this shift in the supply curve<sup>2</sup>. 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 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.<sup>3</sup>

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  $SoXP^*$ , consumer surplus equals the area  $DoXP^*$ , and social welfare is simply the sum of these two areas.

Suppose, though, that the government guarantees the price  $P_d$  to the farmers. If  $P_d$  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  $P_d$ , 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  $P_d$  that it promises farmers and the  $P'$  that

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<sup>2</sup> Economic welfare is defined as the sum of producer and consumer surpluses.

<sup>3</sup> Deficiency payments were eliminated by Congress with the recent passage of the 1996 Farm Bill.

consumers are willing to pay. The result is a deficiency payment equal to the area PdABP'.

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\*XBP' because i) they can still consume the quantity Q\*, but at a lower market price (area P\*XCP'), and ii) they gain additional consumer surplus resulting from the increased consumption (area XCB). Crop producers gain area P\*XAPd because i) they still sell the quantity Q\*, but at a higher price (area P\*XEPd), and ii) they enjoy additional benefits from the increased quantity sold (area XEA). 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 XAB). In summary, the changes in welfare due to deficiency payments (compared to no deficiency payments) are:

Taxpayers:	lose PdABP' (which equals the deficiency payment)
Crop consumers:	gain P*XBP'
<u>Crop producers:</u>	<u>gain P*XAPd</u>
<b>Cost of subsidy to society: lose XAB</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 (equation [5] below)? The answer to this is yes, because deficiency payments did indeed affect prices and quantities in the baseline year of 1990.

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 will define producer surplus with respect to the guaranteed or subsidized price Pd --area SoAPd of Figure 12-2 (see also equation [2] below). We will define consumer surplus with respect to the market price P' -- area DoBP' of Figure 12-2 below (see also equation [3] below). However, because the deficiency payments are a transfer, and not a net benefit, we cannot simply add producer and consumer surplus 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 producer surplus. Therefore, we define net social benefits, or social welfare, as producer surplus

plus consumer surplus *less all deficiency payments (area PdABP')*. The deduction of deficiency payments accounts for the welfare transfer and deadweight loss.

## **12.3 LITERATURE REVIEW**

### **12.3.1 Introduction**

Although the physical effects of pollution on the growth of plants are well-known, the economic impacts of this reduction in crop yield are not. Over the last 15 years, there have been many studies which attempt to estimate the economic effects of reduced agricultural production due to ozone. Some of these focus on 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), while others develop national models (e.g., Kopp et al., 1985; Adams et al., 1986; Adams et al., 1989).

Most of these papers employ 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. First, econometric models are based on actual field data, whereas mathematical programming models usually are based on experimental data for crop yield responses to ozone. Second, 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, and to develop estimates of the economic impact of these reduced yields (Adams et al., 1984; Lesser et al., 1990).

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 cost of all anthropogenic ozone air pollution too, but we also will use a simple model of emissions, air quality, and chemistry, 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 Reviews (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 over 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 National Crop Loss Assessment Network (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<sup>4</sup>; (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 which 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"

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<sup>4</sup> They state "Scenario 1. Fifty percent reduction in the number of hours when O<sub>3</sub> 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)."



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.

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<sub>x</sub>)

IIA) eliminate 10% of motor-vehicle related emissions of ozone precursors;

IIB) eliminate 100% of motor-vehicle related emissions of ozone precursors.<sup>5</sup>

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. 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 (equations [1-4]). The changes in producer surplus and consumer surplus are estimated by solving a constrained surplus-maximization problem. Specifically, we solve a constrained welfare-maximization problem (equations [5a-b]) to find the equilibrium input resource quantities ( $X_{jir}$ ) that maximize total surplus in the crop market, subject to the resource constraints in each region (equation [5b]). Then we substitute these optimal  $X_{jir}$  into a production function (equation [6a] or [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 (equation [7]) in order to find the equilibrium national price for each crop  $P_i$ . We use baseline national data on prices, quantities, and demand elasticities (not the same as the calculated equilibrium price and quantity!) to estimate the intercept ( $\delta_i$ ) and slope ( $\beta_i$ ) of the demand curve (equations [8] and [9] respectively). With estimates of  $X_{jir}$ ,  $Q_{ir}$ ,  $P_i$ ,  $\beta_i$ , and  $\delta_i$ , and given values for resource costs ( $C_{ij}$ ), we use equations [2] and [3] to estimate producer surplus and consumer surplus. We deduct deficiency payments (a federal crop price support program) in equation [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

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<sup>5</sup> We emphasize that we are modeling the benefits due to the elimination of ozone precursor (specifically, VOC and NO<sub>x</sub> 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.

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 (equations [10-12]). 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 model of production and demand is Howitt's (1991b). 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<sup>6</sup>. 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.

The agricultural optimization model includes eight major crops. Consequently, our formal estimates of the agricultural-sector benefits of ozone reduction pertain only to these eight crops. However, after this formal analysis of the cost of ozone damage to eight major crops, we extrapolate our results to account for damage to other crops, and 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) as a result of a change in ozone levels.

#### 12.4.2 The welfare effects of changes in agricultural production

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 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:<sup>7</sup>

$$\Delta W_{USA} = \sum_{r=1}^{12} \Delta W_r \quad [1a]$$

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<sup>6</sup> 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).

<sup>7</sup> 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.

$$\begin{aligned}\Delta W_r &= \Delta PS_r + \Delta CS_r - \Delta DEFPM T_r & \mathbf{[1b]} \\ &= \sum_i (PS_{ir}^b - PS_{ir}^o) + (CS_{ir}^b - CS_{ir}^o) - (DEFPM T_{ir}^b - DEFPM T_{ir}^o)\end{aligned}$$

where

$$PS_{ir}^o = P_i^o Q_{ir}^o + DEFPM T_{ir}^o - MKC_{ir}^o - \sum_j HPC_{jir}^o - \sum_j VIC_{jir}^o \quad \mathbf{[2a]}$$

$$PS_{ir}^b = P_i^b Q_{ir}^b + DEFPM T_{ir}^b - MKC_{ir}^b - \sum_j HPC_{jir}^b - \sum_j VIC_{jir}^b \quad \mathbf{[2b]}$$

and

$$CS_{ir}^o = \frac{1}{2} \cdot (\delta_i - P_i^o) \cdot Q_{ir}^o \quad \mathbf{[3a]}$$

$$CS_{ir}^b = \frac{1}{2} \cdot (\delta_i - P_i^b) \cdot Q_{ir}^b \quad \mathbf{[3b]}$$

and:

$$DEFPM T_{ir} = DP_{ir} \cdot Q_{ir} \quad \mathbf{[4a]}$$

$$MKC_{ir} = Q_{ir} \cdot MKTGCST_{ir} \quad \mathbf{[4b]}$$

$$HPC_{jir} = (X_{jir})^2 \cdot HEDCST_{jir} \quad \mathbf{[4c]}$$

$$VIC_{jir} = X_{jir} \cdot C_{jir} \quad \mathbf{[4d]}$$

(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 12.4.5),

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  $i$  = crop  $i$  (corn, cotton, wheat, barley, alfalfa, soybeans, rice, sorghum; these eight crops account for 63 percent of the total value of U.S. agricultural production<sup>8</sup>, as shown in 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)

$\Delta W_{USA}$  = increase in total economic welfare (net dollar benefits) 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)

$\Delta W_r$  = increase in total economic welfare 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)

$\Delta PS_r$  = 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)

$\Delta CS_r$  = 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)

$DEFPM_{ir}$  = total deficiency payments for crop  $i$  in region  $r$ , estimated at actual ozone levels in 1990 ( $DEFPM_{ir}^o$ ), and reduced ozone levels ( $DEFPM_{ir}^b$ , 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)

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<sup>8</sup> The ninth crop in Howitt's (1991b) model is oats. Because we were unable to locate a dose-response function for oats, we did 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.

- $VIC_{jir}$  = 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 equation [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 equation [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  $r$ . They 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)
- $\delta_i$  = the intercept of the national demand curve for crop  $i$  with the price axis (equation [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 model maximizes producer surplus and consumer surplus in the crop market. (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 crop market:

$$\text{Max}_{X_{jir}} PS + CS = \text{Max}_{X_{jir}} : \quad [5a]$$

$$\begin{aligned} & \sum_i \{ [\delta_i + \frac{1}{2}\beta \sum_r Q_{ir}] \sum_r Q_{ir} \} && \text{Area under the demand curves (from eq. 7)} \\ & + \sum_i \sum_r Q_{ir} \cdot DP_{ir} && \text{plus Deficiency Payments (DEFPMT, from eq. 4a)} \\ & - \sum_i \sum_r Q_{ir} \cdot MKTGCST_{ir} && \text{less Marketing Costs (MKC, from eq. 4b)} \\ & - \sum_j \sum_i \sum_r X_{jir}^2 \cdot HEDCST_{jir} && \text{less Hedonic Program Costs (HPC, from eq. 4c)} \\ & - \sum_j \sum_i \sum_r X_{jir} \cdot C_{jir} && \text{less Variable Input Costs (VIC, from eq. 4d)} \end{aligned}$$

subject to input constraints:

$$\sum_i X_{jir} \leq B_{jr} \quad \text{for all } j \text{ inputs in each region } r$$

[5b]

where:

$$Q_{ir}^o = A_i X_{1ir}^{\alpha_{1i}} X_{2ir}^{\alpha_{2i}} \dots X_{5ir}^{\alpha_{5i}} \quad \text{for all } i,r \quad [6a]$$

$$Q_{ir}^b = \left( 1 + \frac{QGAIN \%_{ir}}{100} \right) \cdot Q_{ir}^o = \left( 1 + \frac{QGAIN \%_{ir}}{100} \right) \cdot (A_i X_{1ir}^{\alpha_{1i}} X_{2ir}^{\alpha_{2i}} \dots X_{5ir}^{\alpha_{5i}}) \quad \text{for all } i,r \quad [6b]$$

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.

$\alpha_{ji}$  = 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  $r$  (derived below; the results for case I, reduction to natural background, are shown in Table 12-5),  
 $\beta_i$  = the slope of the national demand curve for crop  $i$  (equation [8]).

All other parameters are defined above.

**Deficiency payments.** Deficiency payments (equation [4a]) were the result of a federal crop-price support program.<sup>9</sup> Farmers had the option of enrolling 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.<sup>10</sup>

Note that the objective function (equation [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 equation [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 equation [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" (equation [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

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<sup>9</sup> 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.

<sup>10</sup> 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.



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:

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

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

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

*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<sub>ir</sub> (in equation 4b) will not necessarily equal zero. Because of this, and because the MKC<sub>ir</sub> term (equation 4b) is needed for regional estimates, it is included in the model.

In Howitt's model, the parameter MKTGCST<sub>ir</sub> 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 [6a] and [6b] are standard Cobb-Douglas regional production functions. For each region, the values of  $\alpha_{ji}$  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. These data are reported every five years, most recently for 1987. To produce 1990 estimates, we scaled the 1987 regional data by the ratio of 1987 national production to 1990 national production. 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 (equation [6a] for case I, and equation [6b] for case II). Equilibrium prices can then be calculated using equation [7]:

$$P_i = \delta_i + \beta_i \sum_r Q_{ir} \quad \text{for all } i \quad [7]$$

We then use equations [1] through [4] to estimate the welfare changes. (See equations [8] and [9] for the derivation of  $\delta_i$  and  $\beta_i$ ).

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<sup>11</sup>; 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 equation [6b], we assume that for any crop, a given change in ozone causes a constant percentage change in output *for any combination of inputs*.<sup>12</sup> 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%

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<sup>11</sup>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.

<sup>12</sup>Ideally, we would want to treat ozone as another input in the production function.

– 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.<sup>13</sup>

**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 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:

$$\beta_i = \frac{P_i^N \eta_i}{Q_i^N} \quad [8]$$

where:

$\beta_i$  = the estimated slope of the national demand curve for crop i

$\eta_i$  = 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<sup>14</sup>

$Q_i^N$  = the aggregate national (superscript N) baseline quantity of crop i

Given the slope  $\beta_i$ , the demand intercept  $\delta_i$  can be computed by expressing the linear demand equation [7] in terms of  $\delta_i$ :

$$\delta_i = P_i^N - \beta_i Q_i^N \quad [9]$$

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

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<sup>13</sup>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  $\alpha_{ji}$  (elasticity of production of crop i with respect to input of resource j) are assumed to be independent of ozone levels.

<sup>14</sup> These baseline national figures for prices and quantities are used only to derive estimates of the coefficients in the demand equations ( $\beta_i$  and  $\delta_i$ ). The estimated national equilibrium price and regional quantities are used to calculate consumer surplus and producer surplus.

curve; they are not the same as the estimated equilibrium quantities from equations [5] and [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.

#### **12.4.4 Dose-response functions**

A dose-response 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. 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 agricultural optimization model.

**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 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):

$$Q = \mu \cdot e^{-\left(\frac{OZONE}{\gamma}\right)^\lambda} \quad [10]$$

where:

Q = the observed yield

OZONE = the ozone concentration in ppm (air quality data and estimates are discussed below)

$\mu$  = the hypothetical maximum yield at zero ozone

$\gamma$  = the ozone concentration when Q is  $0.37\mu$

$\lambda$  = 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  $\lambda$  equals one and it approaches a linear function when  $\lambda$  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. All but two of the functions assume a Weibull functional form (the other two assume a linear response function). For some crops, we were able to locate more than one yield function: 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 8 of the 9 major crops in the United States.<sup>15</sup>

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

$$QGAIN \%_{ic} = \frac{Q_{ic}^b - Q_{ic}^o}{Q_{ic}^o} \cdot 100 \quad [11]$$

where:

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<sup>15</sup> We did find an SO<sub>2</sub> yield-response function, but it is estimated for crops and conditions in Europe in 1969, and hence is not really applicable to conditions in the U.S. in 1990. In any event, the estimated SO<sub>2</sub> damages are much smaller than the estimated ozone damages.

$QGAIN\%_{ic}$  = 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 equation **[10]** 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 equation **[10]** 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:

$$QGAIN\%_{ir} = \frac{\sum_{c \in r} QGAIN\%_{ic} \cdot QB^o_{ic}}{\sum_{c \in r} QB^o_{ic}} \quad [12]$$

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 equation **[11]**

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

Table 12-5 details the estimated low and high percentage yield changes ( $QGAIN\%_{ir}$ ) for each crop 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 equation [6]). After shifting these functions, we recompute producer and consumer surplus to estimate the net change in economic welfare.

#### 12.4.5 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:

$$\Delta E = f(\Delta P, O) = f(PI, PP, O) \quad [13]$$

where:

$\Delta E$  = the change in the effect of interest (in this analysis, crop yield)

$\Delta P$  = 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 in the U. S. in 1990. 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*  $PI$ :

$$\text{Assume : } \frac{PP}{PI} = \frac{PP^*}{PI^*} \quad [14]$$

$$PP = PI \cdot \frac{PP^*}{PI^*}$$

where:

$PP$  = 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)

$PI$  = the actual ambient ozone level in 1990 (data from air-quality monitors [EPA, 1993]; discussed below)

$PP^*$  = the modeled level of ozone after the change in emissions (summarized below; see Report #16 for details)

$PI^*$  = the modeled level of ambient ozone (Report #16)

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 models of PP\* and PI\*.

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<sub>x</sub> 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).** To specify the initial ozone levels, we use 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<sup>16</sup>.

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.

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<sup>16</sup> We did not have land use information for ozone monitors in 23 counties, and excluded them from our data set.



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<sup>17</sup>.

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 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<sup>18</sup>, 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.

***PP Case I: natural background ozone level.*** In case I, we estimate the agricultural cost of all anthropogenic ozone pollution, which is the difference between current levels and the natural, or “background,” level. The natural level of ozone is a

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<sup>17</sup> A statistical interpolation technique called “kriging” has been used in previous studies to provide average, seasonal O<sub>3</sub> 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.

<sup>18</sup> 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.

function of natural (biogenic) emissions of VOCs and NO<sub>x</sub>, and the injection of ozone into the troposphere from the stratosphere. Thus, we model the natural background (PP\*) in each county c as:

$$PP_{O_3,N,c}^* = C_{VOC',NOx' \rightarrow O_3} \left( \begin{array}{l} (E_{VOC',N,c} \cdot D_{VOC',N,c} + E_{VOC',N,oc} \cdot D_{VOC',N,oc}) \\ (E_{NOx',N,c} \cdot D_{NOx',N,c} + E_{NOx',N,oc} \cdot D_{NOx',N,oc}) \end{array} \right) + PP_{O_3,S}$$

[15]

where:

subscript O<sub>3</sub> = ozone air pollution

subscripts VOC', NOx' = the emitted ozone precursors: nitrogen oxides (NO<sub>x</sub>), and volatile organic compounds (VOCs)

subscript N = natural or biogenic sources

subscript S = stratospheric source

subscript C = the county of interest (i.e., the county for which air quality is modeled and the cost of pollution damage to crops is estimated)

subscript OC = all counties other than county C in the same Air Quality Control Region (AQCR) as C

\* = modeled as opposed to measured air quality

PP<sub>O<sub>3</sub>,N,c</sub>\* = the modeled level of total ambient ozone "received" or formed at air-quality monitors in county C, in a year, due only to natural emissions

C<sub>VOC',NOx' → O<sub>3</sub></sub> = the chemical transformation of VOC and NO<sub>x</sub> to O<sub>3</sub> (a simple nonlinear equation, presented in Report #16)<sup>19</sup>

E<sub>VOC',N,c</sub> and E<sub>NOx',N,c</sub> = yearly emissions of VOCs and NO<sub>x</sub> from natural (biogenic) sources in county C (EPA, 1995a)

E<sub>VOC',N,oc</sub> and E<sub>NOx',N,oc</sub> = yearly emissions of VOCs and NO<sub>x</sub> from natural (biogenic) sources in all counties except C, in the AQCR of county C (EPA, 1995a)

D<sub>VOC',N,c</sub> and D<sub>NOx',N,c</sub> = the fraction of emissions of VOCs and NO<sub>x</sub> from natural sources in county C that reaches the ambient air-quality monitor in county C (estimated on the basis of simple dispersion modeling, presented in Report #16)

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<sup>19</sup> Ozone is formed in the atmosphere from complex chemical reactions involving hydrocarbons, nitrogen oxides, and other chemicals. Because ozone concentrations are a highly nonlinear function of hydrocarbon emissions, our simple nonlinear ozone "model" is quite crude. Nevertheless, this is the only manageable approach. Details are given in Report #16 of this social-cost series.

$D_{VOC',N,oc}$  and  $D_{NOx',N,oc}$  = the fraction of emissions of VOCs and NOx from natural sources in all counties except C, in the AQCR of C, that reaches the ambient air-quality monitor in county C (estimated on the basis of simple dispersion modeling, presented in Report #16)

$PP_{O_3,S}$  = constant injection of ozone from the stratosphere (on the basis of data reviewed in Report #11, we assume a constant stratospheric ozone contribution of 0.01 to 0.015 ppm)

We model  $PI^*$  (in equation [15]) similarly. See Report #16 for details.

**PP Case II: ozone levels with no motor-vehicle related emissions.** In case II, we estimate the cost of motor-vehicle related ozone pollution, by estimating agricultural CS and PS at the ozone levels that would result if emissions of ozone precursors related to motor-vehicle use were reduced by 10% and 100%. We estimate ozone levels without motor-vehicle related emissions with the following simple model of emissions, dispersion, and atmospheric chemistry, developed in Report #16:

$$PP_{O_3,c}^* = C_{VOC',NOx \rightarrow O_3}(P1', P2') \quad [16a]$$

$$P1' = \sum_i EC_{VOC',i} \cdot (1 - MS_{VOC',i}) \cdot \left( D_{VOC',i,c} \cdot OEI_{VOC',i,c} + D_{VOC',i,oc} \cdot \sum_{o \in R_c} OEI_{VOC',i,o} \right) \quad [16b]$$

$$P2' = \sum_i EC_{NOx',i} \cdot (1 - MS_{NOx',i}) \cdot \left( D_{NOx',i,c} \cdot OEI_{NOx',i,c} + D_{NOx',i,oc} \cdot \sum_{o \in R_c} OEI_{NOx',i,o} \right)$$

[16c]

where:

subscripts  $O_3$ ,  $VOC'$ ,  $NOx'$ ,  $C$ , and  $OC$  are as defined above

subscript  $i$  = sources of emissions of  $P'$  (includes all sources in the emissions inventory: motor vehicles, power plants, industries, businesses, farms, and so on).

subscript  $o$  = any county other than  $C$  in AQCR  $R$

subscript  $R$  = AQCR  $R$

$PP_{O_3,c}^*$  = the modeled level of total ambient ozone "received" or formed at air-quality monitors in county  $C$ , in a year

$C_{VOC',NOx' \rightarrow O_3}$  = the chemical transformation of  $VOC$  and  $NOx$  to  $O_3$  (a simple nonlinear equation, presented in Report #16)

$OEI_{VOC',i,c}$  and  $OEI_{NOx',i,c}$  = the EPA's official emission-inventory estimates of emissions of  $VOC$ s and  $NOx$  from source  $i$  in county  $C$  (data from EPA, discussed in Report #16)

$OEI_{VOC',i,o}$  and  $OEI_{NOx',i,o}$  = the EPA's official emission-inventory estimates of emissions of VOCs and NO<sub>x</sub> from source *i* in county *O* (any county other than *C* in AQCR *R<sub>C</sub>*) (data from EPA, discussed in Report #16)

$EC_{VOC',i}$  and  $EC_{NOx',i}$  = our emissions-inventory correction factor, equal to the ratio of our estimate of true emissions of VOCs and NO<sub>x</sub> from source *i* to the EPA's official estimate (discussed in Report #16; this factor is 1.0 for most sources *i*, and is assumed to be the same in every county).

$MS_{VOC',i}$  and  $MS_{NOx',i}$  = the motor-vehicle-related fraction of emissions of VOCs and NO<sub>x</sub> from emissions source *i*; that is, of the emissions of VOCs and NO<sub>x</sub>, from source *i*, *MS* is the fraction that is related to motor-vehicle use (e.g., all tailpipe emissions from motor-vehicles are related to motor-vehicle use; some fraction of refinery emissions is related to motor-vehicle use, and no fraction of emissions from agricultural tillage is related to motor-vehicle use) (estimated in Report #10)

$D_{VOC',i,c}$  and  $D_{NOx,i,c}$  = the fraction of emissions of VOCs and NO<sub>x</sub> from source *i* in county *C* that reaches the ambient air-quality monitor in county *C* (estimated on the basis of simple dispersion modeling, presented in Report #16)

$D_{VOC',i,oc}$  and  $D_{NOx',i,oc}$  = the fraction of emissions of VOCs and NO<sub>x</sub> from source *i* in all counties except *C*, in the AQCR of *C*, that reaches the ambient air-quality monitor in county *C* (estimated on the basis of simple dispersion modeling, presented in Report #16)

We model  $PI^*$  (in equation [15]) similarly. See Report #16 for details.

#### 12.4.6 Crop production data

As discussed above, crop production data are needed to derive estimates of  $QGAIN\%_{ir}$  for each of the 12 crop-production regions from the  $QGAIN\%_{ic}$  calculated at the level of the county. Crop production at the county level is 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 production in 1990 to total 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).

#### 12.4.7 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 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 crop, 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 our model for the three emission-reduction scenarios. (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 only moderately sensitive to ozone, but is by far the most valuable of the eight crops in the aggregate. Alfalfa hay and cotton are very 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 from motor vehicles causes \$2 to \$3 billion in damages to the eight crops (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.

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 Accounting for damages to other crops, and damages from other pollutants

We have estimated in detail ozone damages to eight major crops, which together account for some 63 percent of the total value of U.S. agricultural production. Generally, the crops that constitute the remaining 37% of the total value are not as sensitive to ozone damages as are the eight crops that we have included. However, they are not necessarily completely insensitive to ozone pollution, and in principle must be accounted for in a complete estimate of air pollution damages to agriculture.

How large might the damages to these remaining crops be? We cannot answer this question in the same way that we estimated damages to the eight major crops because the remaining crops do not have dose-response functions, and are not included in Howitt's (1991b) production model. However, the damage to the unestimated crops relative to the damage to the estimated 8 crops must be a function of the value, the market characteristics, the pollution levels, and ozone sensitivity of the unestimated crops relative to the estimated eight crops. For the purpose of getting some idea of the relative damages, we can express this simple relative scaling formally, and make some reasonable guesses at parameter values:

$$W_{u/e8} = V_{u/e8} \cdot M_{u/e8} \cdot OZONE_{u/e8} \cdot QGAIN\%_{u/e8} \quad [17]$$

where:

subscript u/e8 means "of the unestimated crops relative to the estimated eight major crops,"

W = air pollution damage cost (change in welfare due to air pollution),

V = the value of agricultural production = 0.37/0.63 = 0.59,

M = the market characteristics (assume 1.0; discussed below),

OZONE = the average ozone pollution levels (probably about 1.0),

QGAIN% = the average ozone sensitivity (probably not more than 0.10),

The parameter M accounts for the differences in demand elasticities and production functions. For example, if demand for the unestimated crops is relatively inelastic, then the gain in consumer surplus due to a reduction in pollution and increase in output will be relatively large. Similarly, if the supply curves for the unestimated crops are relatively steep, then the gain in producer surplus due to a reduction in pollution and shift in the supply curve will be relatively large. An examination of markets for the unestimated crops might yield some insight into the value of M, but is beyond our scope. In the absence of such an examination, we assume M = 1.0 for our illustrative calculation.

If the unestimated crops generally are grown in the same areas as are the estimated eight major crops, then to a first approximation, the pollution levels will be the same. We assume so here, and hence the parameter OZONE in eq. [7] = 1.0.

We suspect, however, that the unestimated crops are much less sensitive to ozone than are the estimated eight major crops. As shown in Table 12-5, the ozone sensitivity (QGAIN%) of the estimated eight major crops spans more than an order of magnitude. We speculate, then, that the average ozone sensitivity of the unestimated crops is on the order of 10 percent of average ozone sensitivity of the estimated eight major crops.

Putting these assumptions together, we estimate that the damage cost to the unestimated crops is on the order of 5 percent of the damages to the estimated eight major crops. Although this calculation is quite crude and speculative, we believe that the conclusion might be robust.

We would expect broadly similar results from an accounting of the effects of pollutants other than ozone. For example, as noted above, damages from SO<sub>2</sub> appear to be much smaller than damages from ozone.

In the end, we speculate that our detailed estimates of ozone damages to eight major crops accounts for on the order of 80 percent to 90 percent of the total damages to all crops from all air pollutants. Thus, an estimate of the damages to all crops from all pollutants might be 1.1 to 1.25 times our estimated ozone damages to eight major crops.

### **12.5.3 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 upstream 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 the 10% to 25% adjustment factor, for other pollutants and other crops, from equation [7].

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 "upstream" 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub>] results of Table 12-11 hold only for the actual proportions of VOCs and NO<sub>x</sub> 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 10% to 25% scaling factor (from equation [7]), to account for damages to other crops and from other pollutants, applies uniformly to damages estimated for all vehicle classes. But this might not actually be the case. If, for example, these other damages are due mainly to particulate air pollution, then HDDVs, which emit lot of particulate matter, will be responsible for a larger share of total damages than they are of ozone damages alone.

#### **12.5.4 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). 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%<sup>20</sup>.

#### **12.5.5 Conclusion**

We have used an agricultural optimization model 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 damage to other crops, and damage to all crops from all other pollutants, probably do not amount to more than \$0.8 billion. Thus, pollution attributable to motor vehicle use probably causes \$2 to \$4 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 portion of the total cost of air pollution from motor vehicles.

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<sup>20</sup>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.



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**TABLE 12-1. SUMMARY OF RESULTS FROM LITERATURE REVIEW**

<b>Author (Year)</b>	<b>Pollutant (Crops)</b>	<b>Region (Year Analyzed)</b>	<b>P<sup>a</sup></b>	<b>C<sup>b</sup></b>	<b>I<sup>c</sup></b>	<b>Annual Damages c</b>
Adams, Crocker, Thanavibulchai (1982)	Ambient oxidant exposure (14 crops)	Southern California, 4 production regions (1976)	Yes	Yes	Yes	\$46 million benefit current levels to a pollution
Brown and Smith (1984)	Ozone, (corn, wheat, soybeans)	Indiana, 9 production regions	Yes	Yes	No	No welfare calculation substitution e
Mjelde, et al. (1984)	Ozone (corn, soybeans)	Illinois (1980)	No	Yes	Yes	\$226 million loss from a 10% increase in Consumer welfare
Howitt, Gossard and Adams (1984)	Ozone (13 crops)	California, 14 production regions (1978)	Yes	Yes	Yes	\$35.7 million benefit ozone to 0.04 ppb from increasing ozone to \$157.3 million loss ozone to
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 in ozone; \$2.1 billion increase
Adams and McCarl (1985)	Ozone (corn, wheat, soybeans)	"Corn Belt," 5 states (1980)	Yes	Yes	Yes	\$0.7 billion benefit in ozone standard. from increasing

**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 benefit from a 25% reduction; \$98 million benefit from a 50% reduction; 98% attributed to ozone reduction
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 from a 25% reduction; \$1 billion benefit from a 50% reduction for increasing ozone to 0.12 ppm
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; \$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 25% reduction; \$538 million benefit from a 50% reduction; \$1 billion benefit from a 75% reduction
Adams, Glycer, 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 from a 25% reduction; \$3.8 billion benefit from a 50% reduction; \$7.6 billion benefit from a 75% reduction
Howitt and Goodman (1989)	Ozone (43 crops)	California, 17 production regions (1984)	Yes	Yes	Yes	\$50 million benefit from a 25% reduction; \$100 million benefit from a 50% reduction; \$200 million benefit from a 75% reduction



Notes to Table 12-1.

<sup>a</sup>Indicates whether or not price changes are endogenous in the analysis

<sup>b</sup>Indicates whether or not the analysis considers crop substitution as a response to ozone pollution

<sup>c</sup>Indicates whether or not the analysis considers input substitution as a response to ozone pollution.

**TABLE 12-2. AGRICULTURAL PRODUCTION REGIONS**

<b>Regions</b>	<b>States</b>
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. 1990 VALUE OF PRODUCTION FOR THE EIGHT MAJOR CROPS INCLUDED IN THE ANALYSIS (BILLIONS OF 1990 DOLLARS)**

<b>Crops</b>	<b>Value of Production (\$ Billion)</b>	<b>Major Production States</b>
Alfalfa Hay	5.2 <sup>a</sup>	Wisconsin, California, Iowa
Barley	0.9	North Dakota, Montana, Idaho
Corn	18.2	Iowa, Illinois, Nebraska
Cotton	5.1	Texas, California, Mississippi
Rice	1.0	Arkansas, California, Louisiana
Grain Sorghum	1.2	Kansas, Texas, Nebraska
Soybean	11.0	Illinois, Iowa, Indiana
Wheat	7.2	Kansas, North Dakota, Montana
<i>Total - 8 crops</i>	<i>49.8</i>	
Total - all crops	79.8	All (entire USA)
<i>8 crops as a percent of total US crop production</i>	<i>63%</i>	

*Source:* U.S. Department of Agriculture (1992).

<sup>a</sup>Statistics were not available for the value of alfalfa hay. The value of all hay was \$10.5 billion in 1990. Roughly half of both the total hay tonnage and the total hay acres harvested was alfalfa hay, hence we estimate that roughly half of the value of hay in 1990 was alfalfa.

**TABLE 12-4. DOSE-RESPONSE FUNCTIONS**

<b>Crop<sup>a</sup></b>	<b>Equation<sup>b</sup></b>	<b>High/Low<sup>c</sup></b>	<b>Source</b>
Alfalfa Hay	32.67-(1.3902*12hm)	High	Olszyk et al. (1986)
	3010*exp((-12hm/18.7) <sup>1.57</sup> )	Low	Temple et al. (1986)
Barley	1.988*exp((-7h/0.205) <sup>4.278</sup> )	Low = High	Heck et al. (1984)
Corn	314.98-(8.4152*12hm)	High	Thompson et al. (1976)
	13968*exp((-7h/0.160) <sup>4.284</sup> )	Low	Heck et al. (1984)
Cotton	5872*exp((-7h/0.088) <sup>2.1</sup> )	High	Heck et al. (1984)
	367*exp((-7hm/11.1) <sup>2.71</sup> )	Low	Heagle et al. (1979)
Sorghum	8137*exp((-7h/0.296) <sup>2.217</sup> )	High	Heck et al. (1984)
	8149*exp((-7h/0.317) <sup>2.952</sup> )	Low	Kress, et al. (1985)
Soybean	5593*exp((-7h/0.128) <sup>0.872</sup> )	Low = High	Heck et al. (1984)
Rice	exp((-7h/0.2016) <sup>2.474</sup> )	Low = High	Kats and Dawson (1985)
Wheat	5363*exp((-7h/0.143) <sup>2.423</sup> )	Low = High	Heck et al. (1984)

All studies referenced in this table are open-top chamber studies.

<sup>a</sup>Oats are included in the agricultural production model but not here because there is no dose-response equation for oats.

<sup>b</sup>7h refers to the 7 hour mean ozone concentration in parts per million between 9:00 am to 4:00 PM. 7hm refers to the 7 hour mean ozone concentration in parts per hundred 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. 12hm refers to the 12 hour mean ozone concentration in parts per hundred million between 9:00 am to 9:00 PM.

<sup>c</sup>High denotes the equation which generated the high estimate, and low denotes the equation which yielded the low estimate.

**TABLE 12-5. ESTIMATED YIELD RESPONSES (QGAIN%, CASE I) OF THE EIGHT MAJOR CROPS IN THE TWELVE PRODUCTION REGIONS (PERCENTAGE CHANGE)**

<b>Regions</b>	<b>Alfalfa Hay</b>		<b>Barley</b>		<b>Corn</b>		<b>Cotton</b>	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
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

<b>Regions</b>	<b>Rice</b>		<b>Sorghum</b>		<b>Soybean</b>		<b>Wheat</b>	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
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 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**

<b>Crop</b>	<b>Price Elasticity</b>
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**

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

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.

<sup>a</sup>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, CASE I: ELIMINATE ANTHROPOGENIC OZONE-PRECURSOR EMISSIONS (BILLIONS OF 1991 DOLLARS)**

<b>Region</b>	Change in PS <sup>a</sup>		Change in DP <sup>b</sup>	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
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
<b>Total</b>	<b>4.366</b>	<b>11.198</b>	<b>2.312</b>	<b>7.276</b>

Case I is a 100% reduction in anthropogenic emissions of VOCs and NO<sub>x</sub>.

These are the model 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 effects on crops other than the eight, or the effects of pollutants other than ozone (see equation [17]).

<sup>a</sup>PS = producer surplus. Calculated using equations [2a-b]. Includes deficiency payments. See the text for details.

<sup>b</sup>DP = deficiency payments. Calculated using equations [4a]. See the text for details.

**TABLE 12-8B. CHANGE IN PRODUCER SURPLUS AND DEFICIENCY PAYMENTS, CASE IIA:  
ELIMINATE 10% OF MOTOR-VEHICLE-RELATED OZONE-PRECURSOR EMISSIONS  
(BILLIONS OF 1991 DOLLARS)**

<b>Region</b>	<b>Direct Emissions Only<sup>a</sup></b>				<b>Direct + Upstream<sup>b</sup></b>			
	Change in PSC <sup>c</sup>		Change in DP <sup>d</sup>		Change in PSC		Change in DP	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
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
<b>Total</b>	<b>0.251</b>	<b>0.538</b>	<b>0.129</b>	<b>0.341</b>	<b>0.291</b>	<b>0.571</b>	<b>0.152</b>	<b>0.360</b>

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

These are the model 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 effects on crops other than the eight, or the effects of pollutants other than ozone (see equation [17]).

<sup>a</sup>Direct emissions are tailpipe and evaporative emissions from motor vehicles.

<sup>b</sup>Upstream 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.

<sup>c</sup>PSC = producer surplus. Calculated using equations [2a-b]. Includes deficiency payments. See the text for details.

<sup>d</sup>DP = deficiency payments. Calculated using equations [4a]. See the text for details.

**TABLE 12-8C. CHANGE IN PRODUCER SURPLUS AND DEFICIENCY PAYMENTS, CASE IIB:  
ELIMINATE 100 % OF MOTOR-VEHICLE-RELATED OZONE-PRECURSOR EMISSIONS  
(BILLIONS OF 1991 DOLLARS)**

<b>Region</b>	<b>Direct Emissions Only<sup>a</sup></b>				<b>Direct + Upstream<sup>b</sup></b>			
	Change in PSC <sup>c</sup>		Change in DP <sup>d</sup>		Change in PSC		Change in DP <sup>d</sup>	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
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
<b>Total</b>	<b>2.540</b>	<b>5.804</b>	<b>1.233</b>	<b>3.633</b>	<b>2.876</b>	<b>6.111</b>	<b>1.423</b>	<b>3.808</b>

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

These are the model 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 effects on crops other than the eight, or the effects of pollutants other than ozone (see equation [17]).

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 IN ALL REGIONS (BILLIONS OF 1991 DOLLARS)**

	Case I		Case IIA				Case IIB			
			Direct emissions <sup>a</sup>		Direct + upstream <sup>b</sup>		Direct emissions <sup>a</sup>		Direct + upstream <sup>b</sup>	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
Change in PSC <sup>c</sup>	4.37	11.20	0.25	0.54	0.29	0.57	2.54	5.80	2.88	6.11
Change in DPC <sup>c</sup>	2.31	7.28	0.13	0.34	0.15	0.36	1.23	3.63	1.42	3.81
Change in CSC <sup>d</sup>	0.58	1.42	0.03	0.07	0.04	0.07	0.36	0.74	0.41	0.80
<b>Change in welfare<sup>e</sup></b>	<b>2.63</b>	<b>5.34</b>	<b>0.16</b>	<b>0.26</b>	<b>0.18</b>	<b>0.28</b>	<b>1.67</b>	<b>2.91</b>	<b>1.86</b>	<b>3.10</b>

See notes to Table 12-8.

<sup>a,b</sup>See notes to Table 12-8.

<sup>c</sup>From Table 12-8.

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

<sup>e</sup>Equal to  $\Delta PS$  minus  $\Delta DP$  plus  $\Delta CS$ .

**TABLE 12-10. THE CHANGE IN WELFARE DUE TO A REDUCTION IN MOTOR-VEHICLE RELATED EMISSIONS (BILLIONS OF 1991 DOLLARS) <sup>a</sup>**

<b>Case IIA: 10% reduction in emissions<sup>d</sup></b>	<b>Direct emissions<sup>b</sup></b>		<b>Direct + upstream<sup>c</sup></b>	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
LDGAs	0.096	0.186	0.110	0.201
LDGTs	0.041	0.078	0.047	0.085
HDGVs	0.006	0.011	0.007	0.012
<i>All gasoline vehicles</i>	<i>0.143</i>	<i>0.277</i>	<i>0.164</i>	<i>0.299</i>
LDDAs	0.001	0.001	0.001	0.012
LDDTs	0.000	0.000	0.000	0.000
HDDVs	0.028	0.051	0.030	0.054
<i>All diesel vehicles</i>	<i>0.029</i>	<i>0.052</i>	<i>0.031</i>	<i>0.055</i>
<i>All gasoline and diesel vehicles</i>	<i>0.173</i>	<i>0.330</i>	<i>0.196</i>	<i>0.355</i>
<b>Case IIB: 100% reduction in emissions<sup>e</sup></b>	<b>1.839</b>	<b>3.632</b>	<b>2.050</b>	<b>3.874</b>

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 effects on crops other than the eight, and the effects of pollutants other than ozone (see equation [17]).

<sup>a</sup>Equal to change in consumer surplus plus change in producer surplus minus change in deficiency payments.

<sup>b</sup>Direct emissions are tailpipe and evaporative emissions from motor vehicles.

<sup>c</sup>Upstream 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.

<sup>d</sup>Case IIA is a 10% reduction in emissions of VOCs and NO<sub>x</sub>.

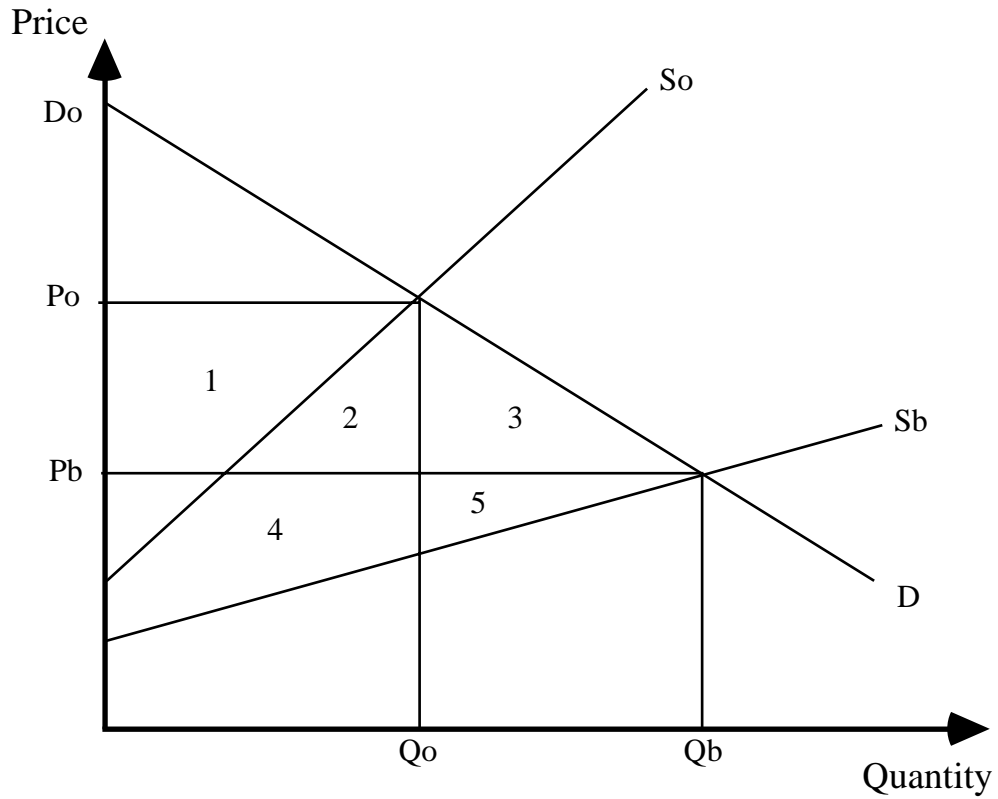
<sup>e</sup>Case IIB is a 100% reduction in emissions of VOCs and NO<sub>x</sub>.

**TABLE 12-11. THE CHANGE IN WELFARE DUE TO A 10% REDUCTION IN MOTOR-VEHICLE RELATED EMISSIONS (1991\$/1000-VMT, AND 1991\$/KG-[NO<sub>x</sub>+VOCs])**

	<b>\$/1000-VMT</b>				<b>\$/kg-[VOCs+NO<sub>x</sub>]</b>			
	<b>Direct emissions</b>		<b>Direct + upstream</b>		<b>Direct emissions</b>		<b>Direct + upstream</b>	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
<b>Case IIA: 10% reduction</b>								
LDGAs	0.62	1.19	0.71	1.29	0.12	0.20	0.11	0.17
LDGTs	1.04	2.00	1.19	2.17	0.13	0.21	0.11	0.18
HDGVs	2.49	4.42	2.85	4.84	0.09	0.15	0.08	0.14
<i>All gasoline vehicles</i>	<i>0.73</i>	<i>1.40</i>	<i>0.83</i>	<i>1.51</i>	0.12	0.20	0.11	0.17
LDDAs	0.23	0.39	0.25	5.02	0.13	0.22	0.12	2.34
LDDTs	0.08	0.15	0.12	0.19	0.13	0.23	0.09	0.14
HDDVs	2.12	3.87	2.30	4.06	0.12	0.21	0.11	0.19
<i>All diesel vehicles</i>	<i>1.68</i>	<i>3.05</i>	<i>1.83</i>	<i>3.21</i>	0.12	0.21	0.11	0.19
<i>All gasoline, diesel vehicles</i>	<i>0.80</i>	<i>1.54</i>	<i>0.91</i>	<i>1.65</i>	<i>0.12</i>	<i>0.20</i>	<i>0.11</i>	<i>0.18</i>
<b>Case IIB: 100% reduction</b>	<b>0.86</b>	<b>1.69</b>	<b>0.95</b>	<b>1.80</b>	<b>0.13</b>	<b>0.22</b>	<b>0.11</b>	<b>0.19</b>

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<sub>x</sub> from each vehicle class and associated upstream emission sources.

**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. 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**

