The Economic Effects of Air Pollution on Agriculture: An Interpretive Review of the Literature

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THE ECONOMIC EFFECTS OF AIR POLLUTION ON AGRICULTURE: AN INTERPRETIVE REVIEW OF THE LITERATURE[a]

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ABSTRACT

The purpose of this document is to provide an economic perspective on the literature concerning the effects of air pollution on agriculture. This literature review examines 1) the adequacy of biological and meteorological information in performing economic assessments, 2) the role of economic theory and methodologies in deriving benefits estimates, and 3) recent published benefit estimates of air pollution control on agriculture. While the discussion of current assessment and implications for future research are limited to agriculture, the empirical and analytical issues reviewed here should be useful to researchers contemplating economic assessments of air pollution to any managed ecosystem.

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1.0: AIR POLLUTION AND AGRICULTURE: REGULATORY AND ECONOMIC PERSPECTIVES

1.1 Introduction

Information on physical and biological responses, including human health, to alternative environmental states form the traditional scientific basis for setting environmental standards. Estimates of the benefits and costs associated with environmental regulation can be used in support of such standards by providing an additional measure of efficiency of environmental management programs. With respect to air pollution control, the Clean Air Act specifically states that regulatory decisions are to be based on human health and other physical and biological science information, not economic efficiency criteria. However, the value of economic information was recently enhanced by President Reagan's Executive Order 12291, which requires that federal agencies consider benefit-cost factors in promulgating regulations. This applies to the U.S. Environmental Protection Agency in implementing the Clean Air Act. In view of the greater importance now attached to economics in regulatory analyses, policymakers need to have some grasp of the strengths and weaknesses inherent in economic benefit analyses.

The purpose of this document is to provide an economic perspective on the assessment literature concerning the impacts of air pollution on agriculture. The objectives include: 1) review the biological and meteorological issues which underly any economic assessment of air pollution effects; such a review will define, from an economist's perspective, the type and quality of biological and meteorological data needed to perform economic assessments of air pollution damage; 2) discuss the role of economic theory and methodologies in deriving estimates of economic benefits; and 3) review recent benefits (or costs of air pollution) assessments in the literature to note conceptual and applied shortcomings; this latter discussion will include a comparison of alternative assessment techniques or procedures as used in measuring benefits of changes in environmental quality and will suggest directions for future research.

The remainder of this introductory section deals with regulatory and background information which justifies economic assessments and includes some general observations on both biological and economic literature. As the title implies, this is an interpretive review; the literature citations and discussions are not exhaustive (although we will reference more literature than we cite) and the judgments rendered are based upon our interpretation of the informational needs of policymakers. While the discussion of present assessments and the implications for further research are limited to agriculture, the empirical and conceptual issues reviewed here should be useful to researchers contemplating economic assessments of air pollution on any managed ecosystem.

1.2 Regulatory Background

The effects of air pollutants on living systems are a major environmental issue in most industrial countries. Pollutants are generally considered as substances which, in sufficient concentrations, produce a measurable effect on man, other animals, vegetation, or materials. Thus, air pollutants may include almost any natural or artificial composition of matter capable of being airborne (Chambers, 1968). Pollutants which are, or have the potential to be harmful to living systems or organisms, include oxides of sulfur (SO_x), oxides of nitrogen (NO_x), particulates, secondary products such as oxidants, and acid precipitation.

Some forms of air pollution are generated primarily by man (anthropogenic sources). Others, such as ozone, occur both naturally and anthropogenically. The recognition of anthropogenic sources of pollutants and their biological and economic effects on managed ecosystems such as agricultural crops and forests provided impetus for air pollution control programs. Federal responsibility for the control of air pollution was formalized in the 1970 Clean Air Act, which assigns specific responsibilities for air quality monitoring and regulation to the U.S. Environmental Protection Agency.

The main objectives of EPA's air pollution control program are public health and safety protection as well as minimizing physical and economic loss. The Clean Air Act, as amended in 1977, mandates EPA to set national ambient air quality standards (NAAQS) for airborne pollutants. Section 108 of the Act specifies that primary air quality standards be set to protect human health, whereas the protection of public welfare is addressed by secondary air quality standards under Section 109. Welfare effects, as defined in the Clear Air Act, encompass effects on vegetation, crops, materials, and economic values. Thus, secondary standards are intended to be set at such a level to prevent actual or anticipated adverse effects to such receptors as vegetation or materials.

It is EPA's legislated responsibility to develop new standards for air pollutants or review existing ones at 5-year intervals based on EPA's research program. The latest scientific knowledge useful in indicating the type and extent of all identifiable effects of the specified pollutant upon public health and welfare are reported in EPA criteria documents (for example, USEPA, 1982a). One of EPA's primary means of obtaining criteria information for setting secondary ambient air quality standards regarding welfare effects is through studies of the impact of various air pollutants to plants (Larsen and Heck, 1976). Although the Clean Air Act specifically precludes setting standards based directly on economic effects, such economic information can provide supporting information to policymakers (Padgett and Richmond, 1983; USEPA, 1982b).

Central to the development of environmental policy strategies is an understanding of the relationship between the benefits and the costs associated with environmental protection. An important implication of Executive Order 12291 is the use of economic information as a basis for choosing among conflicting environmental and economic goals. Neither physical science studies of the effects of air pollutants alone, nor engineering studies of abatement and mitigation methodologies, suggests appropriate levels for precursor emission controls of pollutants. Ultimately, costs and benefits also must be considered. The government and the public are confronted with choosing among varying levels of damages, effects, and costs of control and mitigations, rather than an all-or-nothing choice of "damages or no damages" (Harris and Bangay, 1981). As the public becomes increasingly concerned about whether the costs of environmental control are balanced by the benefits, a consistent means of evaluating tradeoffs among competing economic and environmental goals becomes essential to the decision-making process (Jacobson, 1981; Jaksch, 1980).

1.3 The Link Between Economics and Natural Science

Economic analysis can be an effective tool for comparing the costs and benefits of alternative resource or environmental management policy actions. When correctly formulated, such economic analyses can be useful in estimating the monetary values of vegetation and other receptor losses from air pollution or the welfare consequences of air pollution reductions (Harris and Bangay, 1981; Jacobson, 1981). Economic assessments of air pollution damages typically start with biological information on observed or inferred vegetation quality and/or yield losses for alternative air quality levels. The economic loss or benefit associated with that biological response is then calculated based on the behavior of economic agents as reflected in market information (prices).

To date, the biological information on physical loss estimates has been attained by: 1) experimentally measuring the leaf area damaged or destroyed, 2) determining the loss in biomass or yield through field studies under controlled and ambient conditions, 3) using trained experts to subjectively evaluate the aggregate losses in the field, and 4) using biological and economic models to indirectly estimate yield or value loss (Jaksch, 1980). The estimates are typically obtained under controlled conditions with primary emphasis on response characterized by foliar or visible injury (Mudd and Kozlowski, eds., 1975). The majority of pre-1980 studies on air pollutant impacts on vegetation emphasize the visible or biological changes in the plant following an exposure to air pollution rather than on the economically important consequences of that exposure. For agricultural and silvicultural crops, the relevant economic effects are the reductions in the quantity and quality of marketable products. Subsequent research has indicated that measures of foliar injury cannot easily be extrapolated to levels of reduced plant growth or yield (Jacobson, 1982). To understand effects of ambient air pollution levels on plant growth, yield, and quality, one needs to determine injury thresholds and to establish yield or production response functions representing actual commercial growth conditions for the crops.

The production of biological data amenable to economic analysis was not emphasized until recently (e.g., Heck *et al.*, 1982, 1983). Measuring biological response also requires air quality data expressed in terms relevant to actual crop production. Both pollutant concentration and exposure duration are two variables basic to an understanding of the impact of air pollution on vegetation. The quantitative relationship between the measure of air quality (dose) and the measures of agricultural productivity (response) is described by biologists as a dose-response function. This is somewhat analogous to the production function concept utilized by economists. From the perspective of the botanist, additional factors such as soil type, plant age, temperature, light intensity, and humidity also affect these variables. Since a comprehensive accounting of all these factors may be too complex for practical use, biologists argue for estimation of several of the more important variables for use in setting ambient air quality measurements and criteria (Heck and Brandt, 1976; Jacobson, 1982; Larsen and Heck, 1976). If natural science data are to be used in economic assessments, then the perspective of the economist is needed to guide acquistion of such information. This economic perspective is discussed in detail elsewhere (Anderson and Dillon, 1968; Adams and Crocker, 1982). The review of biological and physical science information, which follows in Section 2.0, focuses on that biological literature meeting the minimum requirements for use in benefits assessment, namely, the generation of response estimates in yield terms and under experimental designs more consistent with field or natural conditions.

2.0: BIOLOGICAL AND PHYSICAL SCIENCE INFORMATION ON AIR POLLUTION AND AGRICULTURE

2.1 Introduction

This section briefly reviews the biological and physical basis for an air pollution effect on agriculture. Material from both the meteorological and biological literature is discussed with primary emphasis given to the latter. The first part of this section identifies atmospheric pollutant precursors. There is limited discussion of the meteorological conditions which facilitate the creation and long-range transport of pollutants. The remainder of the section discusses the biological data base concerning the response of vegetation to air pollution.

Visible plant injury and crop yields reduced by air pollution have been documented in many industrialized nations (Heck and Brandt, 1976). Plant injury from ambient pollutant levels was a major consideration in the adoption of air pollution control strategies. This has motivated numerous assessments of economic losses caused by pollution to the agricultural industry. The ability to measure and monitor ambient pollutant levels has improved in industrialized countries with the advancements in technology. However, there are still conceptual and practical problems in measuring the effects of these pollution levels on agriculture or other ecosystems. This section reviews the state of knowledge on air pollution effects on agriculture and addresses some of the conceptual and practical biological issues relevant to quantifying the effects of air pollutants on agriculture.

Since this is an interpretive review of the literature dealing with the economic impact of air pollution on vegetation, only studies which have attempted to quantify agricultural losses in terms of data amenable to economic analysis are summarized. A detailed review of studies dealing with all types of vegetative effects may be found in the 1978 and 1983 Oxidant Criteria Documents (USEPA, 1978, 1983). Limitations of these studies and an appraisal of the current state-of-the-art with respect to air pollution response functions are reported in the concluding section.

2.2 The Meteorology of Air Pollution

2.2.1 Pollutant Emissions to the Atmosphere

Pollutants which are, or have a potential to be, harmful to vegetation include oxides of sulfur (SO_x), oxides of nitrogen (NO_x), particulates and secondary products such as ozone (O_3), and other photochemical oxidants and acid deposition. Sulfur oxides (SO_x) are believed to be the primary precursor of acid rainfall and are primarily emitted from stationary sources such as utility and industrial boilers burning coal as a fuel. Both stationary and transportation-related sources, such as natural gas refineries, cars and trucks, contribute to nitrogen oxides (NO_x) emissions (USEPA, 1979; Harris and Bangay, 1981). The sources and amounts of these primary pollutants have been studied by researchers in both the United States and Canada (Office of Technology Assessment, 1982; Harris and Bangay, 1981). Anthropogenic emissions of sulfur and nitrogen oxides in the eastern United States increased significantly between 1950 and 1970. Since 1970, however, sulfur oxide emissions have declined while nitrogen oxides have continued to rise (Likens and Bormann, 1974; Office of Technology Assessment, 1982).

Acid deposition and ozone result from the chemical transformation of three primary pollutants: sulfur dioxide, nitrogen oxides, and hydrocarbons (Office of Technology Assessment, 1982). Sulfur dioxide (SO_2) is emitted at phytotoxic levels primarily by anthropogenic sources including power plants and smelters. In addition, the increased combustion of natural gas and motor fuels has increased the amounts of atmospheric nitrogen oxide (NO_x) (USEPA, 1979). After being discharged into the atmosphere, these pollutants can be chemically converted into sulfuric (H_2SO_4) and nitric (HNO_3) acid by oxidation. This complete series of chemical and physical processes occurs during and subsequent to the burning of fossil fuels, ore smelting and petroleum refining. Both sulfuric and nitric acids are identified as precursors to acid deposition (Harris and Bangay, 1981). In summary, acid deposition is a combination of directly emitted or primary pollutants such as gaseous sulfur and nitrogen oxides, transformed or secondary pollutants including sulfates and nitrates, and other chemicals in the atmosphere (Office of Technology Assessment, 1982), whereas ozone (the principal oxidant in ambient air) is the product of photochemical transformation of NO_x and other precursors.

2.2.2 Atmospheric Transport of Pollutants

The fate of a pollutant, once emitted into the atmosphere, depends on meteorological conditions as well as the nature of the pollutant. Some understanding of the transport process is important since most sensitive receptor areas are located at considerable distances from the pollutant source (Harris and Bangay, 1981; Likens and Bormann, 1974).

Several meteorogical factors account for the large-scale movement of pollutants within and between the United States and Canada. The westerly wind pattern prevailing over much of the eastern United States and Canada is complicated by seasonal trends which include a southerly direction in the summer and a northerly direction in the winter. Both high winds and a stable lower atmosphere, where the temperature increases with altitude, aid in the transport of air pollutants including sulfur and nitrogen oxide emissions. Also, the absence of precipitation increases the distance air pollutants are carried.

With particular emphasis given to SO_2 (the main source of acid deposition), Likens and Bormann (1974) described the impact of air pollution control technologies on the large-scale movement of pollutants between regions. Until the 1950s, most of the atmospheric sulfur from combustion of coal was deposited on land near the combustion source in particulate form and neutralized salts. Two factors associated with air pollution control have helped transform local "soot problems" into a regional "acid rain problem": the installation of particle precipitators and the increased height of smokestacks. When emitted at heights between 60 and 360 meters, the SO_2 may be dispersed over large areas; and in the absence of equivalent amounts of alkaline substances in the atmosphere, appreciable amounts of SO_2 are converted into sulfuric acid (H_2SO_4). Likens and Bormann (1974) conclude that the consistently low pH of precipitation at rural sites in New England located hundreds of kilometers from urban industrial areas, may be caused by the long-range dispersion of SO_2 and its secondary pollutant, H_2SO_4.

Similar implications are drawn by Altshuller (1976) in an analysis of the distribution of concentrations of sulfur dioxide (SO_2) and sulfate ($SO_4{}^2$) at 48 urban sites and 27 non-urban sites throughout the U.S. for the period 1963 to 1972. Data from these sites indicated that while the urban to non-urban SO_2 concentration gradient ranged from 5:1 to 10:1, the urban to nonurban $SO_4{}^2$ concentration was about 2:1. Thus, changes in the patterns of SO_2 emissions between air quality regions resulted in no differences between ambient sulfate concentrations in the same air quality control regions. Higher ambient sulfate levels were concentrated in eastern air quality control regions. Between 75 and 90% of sulfate depositions in any state in the eastern half of the United States originate outside the state. These observations can be explained by the chemical conversion of SO_2 to sulfates occurring over ranges of hundreds of kilometers. The impact of the long-range transport of sulfates emphasizes the need for consistent strategies to reduce sulfur oxide levels throughout large geographical areas.

As previously noted, ozone is not emitted directly into the atmosphere by pollution sources, but is produced as a result of photochemical transformation of nitrogen oxides and hydrocarbons. Past research indicates that ozone alone or in combination with sulfur dioxide and nitrogen dioxide is responsible for up to 90% of air pollution-related crop damage in the United States (Heck _et al._, 1982). Many regions with elevated ozone concentrations, such as southern California and the Midwest, are major agricultural production regions. It is not known how much crop damage is caused by transported, rather than locally produced, ozone concentrations (Office of Technology Assessment, 1982).

Investigation of the generation, buildup, and dissipation of ozone concentrations in the atmosphere over the Los Angeles Basin and Eastern North America has underscored several recent studies. Based on a summary of past research, Niemann (1983) identifies the following sources contributing to the presence of ozone at any given location: 1) natural or "background" ozone, including stratospheric intrusions; 2) ozone generated from anthropogenic sources; 3) ozone associated with accumulation in high barometric pressure weather conditions (anticyclones) and subsequent long-range transport; and 4) ozone formed in urban plumes downwind of industrialized centers. Past analysis of monitoring data does not reveal each source's contribution to ozone; further, Niemann (1983) notes that a general photochemical transport model that includes all four sources has not been developed.

In an attempt to single out the primary cause of ozone concentrations occurring over large areas, Niemann (1983) studied basic source-receptor relationships in terms of ozone precursor emissions, stagnating anticyclones, average ozone concentrations and terrestrial resources-at-risk (i.e., agricultural crops). By utilizing current emissions, monitoring data bases, and historical meteorological data bases, it was found that the area of highest average ozone concentrations did not occur over or downwind from areas of highest precursor emissions. The frequency of stagnation is the greatest over southern Appalachia, where the highest ozone concentrations were found. This result suggests that accumulation and transport in stagnating anticyclones are major contributors to producing the highest long period average ozone concentrations in eastern North America. This is particularly relevant to the study of air pollution induced vegetation effects because the areas of highest average ozone concentrations and stagnation coincide with major agricultural production regions and the boundaries of the eastern deciduous forest ecosystem.

Areas experiencing acid deposition (elevated levels of hydrogen ions) are also major agricultural centers such as the Corn Belt (Office of Technology Assessment, 1982). Although the impacts of acid deposition on agricultural productivity has only been documented under simulated conditions (Lee et al., 1981; Evans, 1982), there is a potential for a pollution problem. Specifically, most of the agricultural counties (counties with more than 30% agricultural land area) in the Corn Belt experience elevated hydrogen ion deposition. Further, many of these counties also have high ozone concentrations, illustrating the considerable amount of regional similarity between elevated levels of both pollutants (Shriner et al., 1982). This correspondence between areas of highest average ozone concentrations and stagnation and major agricultural production regions and the boundaries of the Eastern deciduous forest ecosystems was also reported by Niemann (1983).

In summary, secondary air pollutants include sulfates, nitrates, and ozone and have several factors in common: 1) they can form over periods of hours to days and travel hundreds to possibly thousands of kilometers; 2) they can only be controlled indirectly by controlling the primary pollutants from which they are produced (or intermediaries that determine their rate of transformation); 3) different secondary pollutants result from the same primary pollutants -- for example, nitrogen oxides can react to form both nitrates, a component of acid deposition, and ozone; and 4) they manifest themselves in several ways -- for example, sulfate is a precursor to both acid deposition and visibility reduction (Office of Technology Assessment, 1982).

2.3 Biological Basis for Air Pollution Damages

2.3.1 Mechanisms for Damage

The primary entrance of gaseous pollutants is through the stomata located in the plant's leaves. Factors which affect stomatal opening (i.e., light, water stress, and even pollutant history) ultimately control the internal dose which the plant experiences (Kercher et al., 1982). At the plant level, these physiological changes may ultimately be expressed as foliar injury, premature senescence, reduced plant vigor and plant growth, altered product quality and reduced plant yield (Heck and Brandt, 1976; Mudd and Kozlowski, eds., 1975; Heck et al., 1982).

Response of vegetation to air pollution can be either visible or hidden. Visible injury is seen most distinctly on leaves. Symptoms include identifiable morphological, pigmented, chlorotic and necrotic foliar patterns resulting from major physiological disturbances in plant cells. Foliar symptoms are unreliable indicators of oxidant effects on plant growth or yield because photosynthate is unequally allocated in the plant metabolism and because the plants can rapidly recover from injury (Jacobson, 1982).

Although subtle pollution effects may not be manifesting visible symptoms, they can be measured through observed growth or physiological changes in the plant. These effects include reductions in photosynthesis, biomass, nutritional content, color, texture, flavor, etc., of the plant product (Heck and Brandt, 1976; Heck et al., 1980).

To assess economic losses caused by air pollution, a distinction must be made between injury and damage or loss. Injury is any identifiable and measurable response of a plant to air pollution while damage or loss is any identifiable and measurable adverse effect upon the desired or intended use of the plant. Leaf necrosis is an example of injury; to be classified as damage, the injury must affect yield or use. Therefore, metabolic changes that accompany low pollutant concentrations might not cause visible injury but may cause damage or economic loss (Halvorsen and Ruby, 1981; Heck and Brandt, 1976). This distinction is especially important in evaluating economic effects on yield and marketability of agricultural and horticultural plant products.

2.3.2 Factors Affecting Plant Responses

The effect of air pollutants on vegetation depends on the duration and concentration of exposure as well as biological and environmental factors. Concentration and duration of plant exposure may be either acute or chronic.

Acute response is frequently accompanied by visible injury, but may not necessarily result in significant yield reductions. The subsequent development of necrotic foliar patterns tend to be characteristic of a given pollutant. Acute symptoms are associated with short-term exposures to varying pollutant doses and usually appear within 24 hours after exposure. The severity of injury varies from species to species and depends on leaf age, soil characteristics, and other interacting factors such as rainfall and temperature. Chronic injuries, associated with long-term or intermittent exposure to lower concentrations of a pollutant, are generally less specific and often resemble symptoms caused by parasitic diseases, insects, senescence, nutritional imbalance or other environmental stresses (Heck et al., 1980; Leung et al., 1978). Pollutants may cause quantitative and/or qualitative changes in crop growth and eventually yield without any visible foliar injury (Heck, 1976; Jacobson, 1982).

Plant response is also affected by environmental variables before, during, and subsequent to pollutant exposure. These effects have been documented in the laboratory under controlled conditions and more recently confirmed by field studies (Heck and Brandt, 1976; Heck, 1977; Leung et al., 1978). Environmental and biological factors affecting plant sensitivity to air pollutant exposures are summarized in Table 2.1. Of the factors affecting plant response to air pollution, inherent genetic resistance is probably the most important single factor. Environmental factors affecting plant sensitivity are likely to include those parameters influencing stomatal aperture size. Plants are more resistant to pollution when their stomata are closed;

Table 2.1. Factors Affecting Plant Sensitivity to Air Pollutant Exposures

Biological Factors:	Genetic Composition Stage of Development
Climatic Factors:	Light Quality Light Intensity Precipitation Temperature Relative Humidity Carbon Dioxide
Edaphic Factors:	Soil Moisture Soil Type Soil Nutrients
Production Input Factors:	Irrigation Fertilizer Cultural Management Practices
Other:	Plant-Pollutant Interactions Plant-Pathogen Interactions

Adapted from: Heck and Brandt, 1976; Moskowitz and Medeiros, 1982.

therefore, they are better able to handle exposure at night and at lower temperatures. Susceptibility to ozone increases as relative humidity rises and at certain stages of plant development, such as flowering (Heck and Brandt, 1976). These factors are thought to affect the response of agricultural crops to air pollution by 20 to 50% percent (Kercher *et al.*, 1982).

2.3.3 Assessments of Agricultural Damage

The majority of earlier assessments of air pollution damage to vegetation relied primarily on the reporting of physical changes (foliar injury) sustained by the specific plant (e.g., Middleton and Paulus, 1956; Weidersaul and Lacasse, 1972; Feliciano, 1971; and Millecan, 1976). These assessments are based on subjective evaluations from field observations or extrapolations from controlled studies of plant foliar response to the pollutant. In either case, the foliar response is used as a surrogate for yield response.

Although the markings on the leaves of a plant may be associated with a specific pollutant, it is often difficult to measure the actual physical loss in plant yield. Therefore, most plant studies before 1978 are generally not relevant to assessing economic impacts of air pollutants. They can, however, provide qualitative evidence upon which to develop hypotheses concerning yield, which is related to economic effects, as well as to identify both sensitive and resistant plants for particular pollutants (Heck and Brandt, 1976; National Academy of Sciences, 1977).

To assess agricultural damages in yield terms and ultimately the economic consequences of such damages requires some measure of direct yield effects on crops. These types of response studies are found in the most recent air pollution literature (e.g., Heck et al., 1982).

Here, the effects of air pollutants on vegetation, as measured in physical yield loss, is manifested in data collected: 1) in greenhouses, 2) in other controlled environmental field chambers (either open- or closed-top), and 3) in the field. There are important advantages and limitations to each of these approaches.

Until recently, it was assumed that air pollutant effects on plants grown in controlled indoor environments would parallel field responses. Recent experiments, however, indicate that responses of crops grown under different environmental conditions may be qualitatively similar but quantitatively different (Heck et al., 1980).

Since chamber experiments can control most environmental conditions, they provide a means of assessing the effect of variations in one or two pollutant levels on yields. An open-top chamber appears to be preferred to a closed-top and a greenhouse because it most closely simulates actual field conditions. Air flow is the only affected variable in an open-top chamber, whereas a closed-top chamber affects air flow and precipitation. The total environment is affected in a greenhouse (Heagle and Heck, 1980).

Field observations provide information under ambient conditions without extrapolation from a controlled or artificial environment. Observed field responses, representative of ambient air pollution conditions and cultural practices, provide the most realistic data for use in economic assessments. Unfortunately, the lack of controls (unexposed plants), the number of factors that fluctuate with time (temperature, light, precipitation, etc.), and the non-homogeneity of plants and conditions, may confound attempts to identify effects of a single parameter (Harris and Bangay, 1981; Moskowitz and Medeiros, 1982).

To estimate economic losses to crops caused by air pollution, a measure of actual or predicted yield loss reflecting real world production conditions and constraints is needed. An approximation to this desired measure can be derived from a dose-response function based on experimental field data collected across varying levels of air pollutant exposure. Economic assessments can also be conducted utilizing producer behavior on costs and output as an indirect means to arrive at yield adjustments caused by pollution (Dixon et al., 1983). Because the feasibility of these techniques is limited by the availability of specific data, greater weight is placed on experimental data and dose-response functions as a source of information on yield effects for use in economic assessments (Adams, 1983).

The remainder of this section discusses "the state-of-the-art" in response estimation as portrayed in the dose-response literature. The majority of the recent response literature deals with ozone, given its role as the primary pollutant causing crop losses in the United States. Within this literature, EPA's National Crop Loss Assessment Network (NCLAN) research program, which focuses on the identification and estimation of dose-response functions for major agricultural commodities, has become the major source of response information for use in standard setting. This recent emphasis on dose-response functions within the air pollution vegetation literature signals a departure from the traditional analysis of variance designs used by botanists studying air pollution. Such a departure is necessary if these studies are to provide more realistic input into the standard setting process as well as into economic assessments of air pollution. Even though the dose-response experimental designs abstract from some important economic and environmental variables found in a production function specification (Heady and Dillon, 1968), the resultant functions can predict hypothetical yield adjustments under restrictive conditions. Although plagued with conceptual shortcomings, this type of information is of value simply because it is the most defensible information available for many types of crop responses.

2.4 A Review of Ozone Yield Effects

Injury caused by photochemical oxidants near urban areas was first described in 1944 (Middleton et al., 1950). Ozone also injures plants in rural areas quite distant from large urban centers. Research and field observations indicate that O_3 alone, or in combination with SO_2 and NO_2, is responsible for up to 90% of the crop loss in the United States caused by air pollution (Heck et al., 1982). Thus, ozone has the potential to cause substantial economic damage. This section reviews some of the findings by plant species or cultivar.

Experimental studies with O_3 provided further evidence that reductions in yield occur for such crops as beans, tobacco, potatoes, onions, radishes, grapes, corn, and others (Heggestad, 1980; Jacobson, 1980; Reinert, 1975). A review of these studies indicates that frequent exposure during the growth season to O_3 concentrations in excess of 0.1 ppm may produce yield reductions of at least 20% for susceptible crops (Harris and Bangay, 1981).

The need for plant response information measured in terms of yield rather than injury has been noted by most economists doing assessment research (Adams et al., 1979; Jaksch, 1980; Leung et al., 1978). Some plant scientists have also recognized the need to report response in terms of yield if realistic economic losses are to be estimated. For example, Oshima et al. (1976) conducted a cross-sectional analysis of field plot data on the relationship between ozone and alfalfa in the South Coast Air Basin of Southern California. Interactions between ozone concentrations and alfalfa (variety Moapa 69) yield loss were examined using nine standardized field plots grown with an ambient ozone gradient in this region. Results indicated that ambient ozone dose had a statistically significant effect on the percentage reduction in harvestable yield of alfalfa. Analyses were subsequently developed, assuming a number of different exposure thresholds.

A dose-response function relating ambient O_3 dose to the harvestable yield of fresh market tomatoes was also estimated by Oshima et al. (1977). Similar to the study on alfalfa, the Oshima rsearch showed ozone had a statistically significant impact on yield but the temperature and relative humidity variables were not significant factors.

Open-top chambers have been extensively used by the U.S. Environmental Protection Agency in the NCLAN program to examine effects of ozone on crop yield. These chambers permit crops to be exposed to different pollutants under minimally altered field conditons (Heck et al., 1982).

In the NCLAN program, the impacts of ozone on major agricultural crops (corn, soybean, grain sorghum, lettuce, peanut, barley, cotton, beans and wheat) are studied at different sites in the United States. Within the chambers, crops were exposed to a range of ozone concentrations, whose daily variation was determined by the changes in ambient ozone concentration continuously monitored at the respective site. In the analyses, Heck et al. (1982) utilized analysis of variance and regression techniques to identify relationships between the seasonal 7 hour per day mean ozone concentrations and crop yield. Initially, a linear regression equation of the form $y = b_0 + b_1x$, where y = yield in grams/crop and x = seasonal 7-hour per day mean ozone concentration, was used to develop the general percent yield reduction models. Alternative model specifications are also tested, including the quadratic, linear-plateau, and Weibull. Greatest weight is given to the Weibull model specification of the relationship between dose and yield. Each crop's percent reduction in yield can be expressed in a general equation: $Y = \frac{100\ b_1}{a}(X_0 - x_1)$, where y = predicted percent yield reduction, b_1 = the regression coefficient from the yield Model, a = the predicted yield at a seasonal 7-hour per day mean ozone concentration of X_0 parts per million (ppm) and x_1 = assumed seasonal 7 hours per day ozone concentration. Thus, the individual response models can be used to assess the percent yield reduction for each crop by comparing the predicted yield at a given ozone concentration relative to the predicted yield for an assumed or hypothetical seasonal 7 hour/day mean ozone level. The results of the regression analyses for three crop years and 15 crops may be found in Heck et al. (1982) and Heck et al. (1983). In Heck et al. (1983) and in Adams et al. (1983) these yield reduction models are used to compare current production (associated with the present federal ambient ozone standard) with alternative assumptions concerning improvements or degradations in regional ozone concentrations.

2.5 Acid Deposition: Possible Effects on Vegetation

All precipitation contains a wide variety of chemical constituents from sources such as dust particles, sea spray, and the natural cycling of carbon, nitrogen, and sulfur. The discharge of wastes to the atmosphere increases the amounts of compounds containing these elements. Four ions are of most importance to rainfall acidity: hydrogen (H^+), ammonium (NH_4+), nitrate (NO_3-), and sulfate (SO_4^{2-}). The addition of the hydrogen, sulfate, and nitrate ions to soil and vegetation may have both beneficial and deleterious effects. Excessive acidity that may interfere with physiological processes and reduce growth and yield has been attributed to the hydrogen ion. Although direct harmful effects on vegetation have been linked to the hydrogen ion concentration, both sulphate and nitrate depositions provide fertilizer to the soil, and thus can be considered as nutrients in support of plant productivity (Jacobson, 1980; Office of Technology Assessment, 1982). The net effect of these opposing influences appear to vary with plant species and cultivars, stage of plant development, pattern and timing of rainfall applications, soil nutrient supply, and probably other factors as well (Jacobson, 1981; Lee et al., 1981).

The application of simulated acid precipitation to various crops and forests under controlled conditions has produced both positive and negative results. The effects documented in previous experimental studies utilizing simulated acid rainfall are summarized in the Critical Assessment Document (USEPA, 1982a). Visible foliar symptoms can be produced on certain crops when the pH of the applied rain is 3.5 or less. Jacobson (1980) reports that field-grown plants may be less susceptible to the development of foliar injury than plants grown under controlled or semi-controlled environments. Further, as with ozone, foliar symptoms may not correlate closely with yield reductions (Lee *et al.*, 1981). There are no confirmed reports of exposure to ambient acid precipitation causing foliar symptoms on field-grown vegetation in the continental United States (Jacobson, 1980).

The following summary of knowledge about the effects of acid deposition on crops is reported by the Office of Technology Assessment (1982): (1) visible injury thresholds for acid precipitation lie between pH 2.0 and 3.6, depending on species, and may vary from pH 3.0 to 3.6 within the same species (i.e., bean); (2) species-to-species variability in sensitivity may range two pH units; (3) the threshold for growth effects in the absence of visible injury is reported to be between pH 3.5 and 4.0, but sulfur and nitrogen inputs from deposition may result in a net positive growth impact depending on soil nutrient status, buffer capacity, plant nutrient requirements, and other growth conditions; and (4) total dose of acidity appears to be most clearly related to visible injury.

2.6 Estimating Plant Response to Pollution

2.6.1 The Biological Perspective

To perform credible economic assessments, information is needed on changes in crop yield at pollutant doses representative of ambient air and other climatic and edaphic (soil-based) conditions of agricultural production regions. What is an acceptable level of resolution or precision in actual estimates depends on the use for which those estimates are intended. Heagle and Heck (1980) identify the following components of an "ideal" dose-response methodology from the perspective of the plant scientist: (1) an accurate means to control and measure the pollutant concentrations; (2) treatment with all concentrations under the same environmental conditions; (3) the identification, understanding and control of all factors affecting sensitivity; and (4) a biologically relevant way to report the pollutant dose. To determine effects at different doses (a dose-response curve), the effect of at least four doses (three plus a control) should be tested under the same environmental conditions. Further, the pollutant concentrations and exposure durations should include those likely to occur in the ambient atmosphere of different regions. Heagle and Heck (1980) conclude that the highest dose should give a response in the 30 to 70% range so a reasonable dose-response curve can be drawn.

Such a perspective reflects the concerns of those in plant science or other replicative sciences for control of as many exogenous factors as possible. While such concerns are a legitimate manifestation of the disciplinary integrity of plant science, the structure imposed by the experimental design tends to provide yield information which is somewhat removed from responses observed under commercial conditions and hence limits the range of economic responses over which an economic assessment may be calculated. To understand why, the next section presents the economist's perspective on the issue.

2.6.2 Estimation of the Response Surface: An Economic Perspective

The concept of an air pollution dose response function is central to the assessment of biological damages associated with air pollution. Analogous to the economist's production function, both concepts require that issues such as the appropriate measures of pollution dose, the algebraic form of the structure to be estimated, and the roles of other covariates be addressed (Adams and Crocker, 1982). For the biological scientist to acquire economically informative dose-response data for assessment of the bioeconomic consequences of pollution, the economist must specify relevant data needs. Key concepts in providing guidance to the biological scientist include the delineation of the economically relevant region of the response or production surface and the possibility for and extent of input substitution in the production processes. Specifically, Adams and Crocker (1982) note that the following issues are pertinent to the study of air pollution ecosystem response surfaces: (1) the design of the response surface experiment; (2) the estimation of these surfaces; (3) the choice of models to represent the surface; and (4) the sources of discrepancies between response surfaces estimated in controlled or experimental conditions and observed under field conditions.

2.6.2.1 Experimental design

The importance of biologically based information in economic assessments tends to increase as the investigator moves from the study of managed ecosystems associated with agriculture to more complex natural systems, because producer adaptations play a lesser role in the latter. Unfortunately, much biological research into response surface questions is of limited use to the economist because of the use of analysis of variance techniques to establish only whether there exists statistically significant differences in the output obtained from a few levels of a single input. In the estimation of a response surface, economists are more concerned with statistical comparisons of performance across alternative models rather than the replicative results attained by biologists.

There are at least three conditions which should suggest an appropriate response surface experimental design. First, the greater the sensitivity of the system being studied to variation in exogenous parameters, the greater the desirability of additional replication. Second, there is a need for greater density and breadth of coverage of the economically relevant regions of the response surface when the number of exogenous influences upon system behavior increases. Third, research should be centered on denser coverage and greater replication along the steeper parts of the economically relevant portions of the response surface as it is along these areas that outputs are most sensitive to input mixes and magnitudes.

2.6.2.2 Estimation of the response surface

The appropriateness of available statistical methods for estimating response surfaces is well understood by biometricians. However, when human decision-making plays a role in the response of a system (such as agriculture) to pollution, then any estimated statistical parameters obtained from a problem specification or structure which ignores such human responses are potentially biased. For example, an estimated response expression based on purely biological constraints which relates the effect of additional factors thought to influence a system's response to air pollution may not be appropriate to establishing a pollution response surface since substitution possibilities and agent adaptations are ignored. Because some human decision variables both influence and are influenced by dose-response relations, prior economic analysis is necessary to the specification of the response expressions in an interpretable form. This again argues for communication between the natural scientist and economist during the conceptualization of an experimental design.

2.6.2.3 Choice of models

Any estimation of a response function or surface requires a specification of the functional form or model by which the dependent and independent variables will be linked. A model which explicitly accounts for all the factors known to influence a system's sensitivity to air pollution will be more complex than a simple model which only relates the effect on the system caused by a change in an environmental variable. In most cases, a trade-off exists between model generality or elaboration and measurement error. Since the precision in model parameter estimation declines in the presence of correlation between explanatory variables (the statistical problem of multicollinearity), a simple model may provide a more precise measure of the response estimates. Also, simple models may be adequate in estimating ecosystem response to pollution in the absence of interactions among excluded explanatory variables. Conversely, exclusion of variables may bias the response coefficient. Ultimately, the issue of trade-offs between simple and complex models can only be resolved empirically.

2.6.2.4 Experimental versus field response surfaces

As summarized by Adams and Crocker (1982), two factors appear to account for the discrepancies between experimentally derived and field observed response surfaces. The first relates to the removal of all influences affecting plant response in controlled experiments except for pollutant dose. Factors which are assumed to influence plant response tend to be set at biologically optimal levels to remove confounding sources of stress. Given that these biologically optimal levels exceed those found in natural ambient environments, one can infer that they are less binding, implying, by the Le Chatelier principle (Silberberg, 1978), that the contribution of a positive input (i.e., a pollution reduction) to plant response will be greater than it otherwise would be.

The second reason arises from the role that producer adaptations in response to yield variability (or risk) plays in managed ecosystems, such as an agricultural system. All feasible sources of random variation in output levels are excised under strictly controlled experimental conditions, whereas, in field conditions, the agricultural manager must adapt his activities to natural sources of random variation such as weather, insect infestations, and air pollution.

As Just and Pope demonstrate, the input mixes and magnitudes the farmer selects influence both the levels of output in any one-time interval and the variability of these levels over time. Thus, for example, if the land area for which a farmer is responsible increases and there are no more inputs (e.g., lime, fertilizers, labor) than before, the susceptibility of his crops to pervasive air pollutants such as acid deposition or oxidants will also increase. (Increasing land area when faced with the possibility of highly localized air pollution episodes will have the opposite effect through spreading of the risk.) In taking countermeasures to such a pollution event, the farmer has to spread the same inputs over a greater area. The implications of this as a source of discrepancies between experimentally derived and field observed response surfaces become apparent with the following simple argument:

Consider a risk neutral, net revenue maximizing farmer who must make all his input commitments before the start of any single growing season. For simplicity, further assume that air pollution over the growing season is expected to be either high (α) or low (β). If air pollution is high, the marginal cost of applying various crop yields, given the input commitments already made, will be represented by the $(MC|\alpha)$ curve in Figure 1. This curve is the highest of the three marginal cost curves because the actual occurrence of the α level of air pollution will reduce the marginal products of the preselected mix of inputs, and thereby increase the marginal cost of producing any particular yield. On the other hand, if realized air pollution levels during the growing season were β, then, in accordance with the $(MC|\beta)$ curve, the marginal cost of producing various yields would be reduced. The MC^o curve is simply the probability weighted average of $(MC|\alpha)$ and $(MC|\beta)$.

If, for simplicity, the farmer regards the occurrence of either α or β air pollution as equally likely, then MC^o is the marginal cost curve associated with the input mix maximizing his expected net revenues. Although this input mix will, on average, yield x^o during any one season it will result in yields of either x^α or x^β. Thus, if air pollution is high during one season, x^α will result; if it is low, x^β will result. In effect, the variability in levels of air pollution causes yields in areas sometimes subjected to air pollution to be more variable than in areas where air pollution never affects yields or where it is always at a high level. Thus, for given input mixes, the odds of discrepancies between experimentally derived response surfaces and field observed response surfaces are greater in regions subject to fluctuating levels of air pollution.

If maximum air pollution levels have been increasing over time, then one would expect yield variability to increase in those areas where air pollution has been increasing. This is because the lowest level of air pollution (zero) cannot be altered, while the highest level has increased, causing the $(MC\ \alpha)$ curve to shift upward. Unless the farmer constantly lives in the darkest depths of despair about the air pollution problem, the MC^o curve, which is a probability weighted average of the other two curves, will never shift upwards

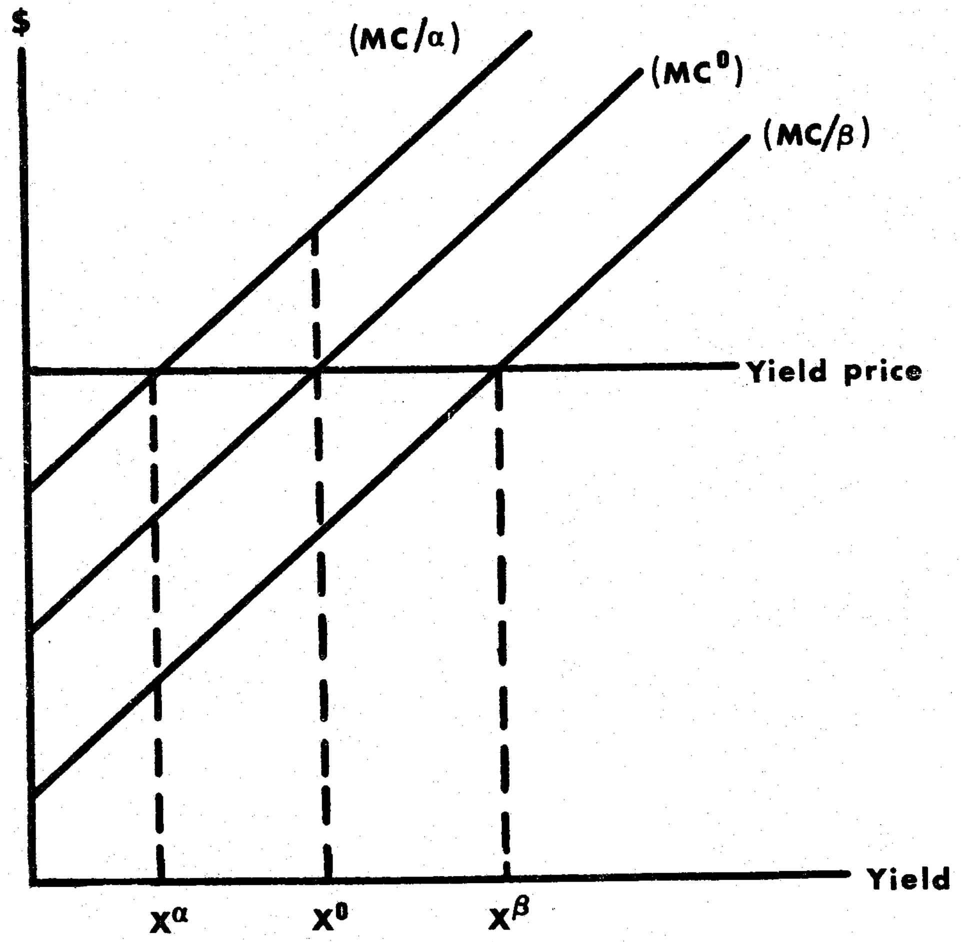

Figure 1. Effect of air pollution upon yields.

as much as the (MC α) curve. This result will be increasing yield variability over time. Consequently, discrepancies between experimentally derived response surfaces and time series of field observed surfaces are likely to be greater where levels of air pollution have historically been increasing.

These issues underlying response estimation indicate some fundamental differences between the perspective of the natural scientist and the economist in terms of experimental design. The impact these differences have on research output can be minimized through coordination of effort, as exemplified by close working relationships typically found between agronomists and economists in the Land Grant University setting. The natural scientist needs to recognize that the output of their experiments may go beyond basic research. Where these data are to be used in policy analysis or assessments, then the perspective of the economist has something to offer.

2.7 Appraisal of Dose-Response Literature

This review and evaluation of the current data sets on ozone and acid deposition effects on agricultural crops reveal several limitations on biological and economic utility. The first involves a lack of coverage of major perennial crops and tree species in studies of the sensitivity of crop yields to pollutants. Although the information base for ozone effects on annual crops is expanding rapidly through NCLAN (Heck *et al*., 1982, 1983), only limited evidence of plant response is available for acid deposition (Lee *et al*., 1981). Secondly, the dose-response functions need to be estimated across levels of ozone and acidity that relate to ambient conditions found in the major production regions, rather than elevated levels which may lie beyond levels anticipated under present control progams.

The third issue concerns the need to account for some edaphic and climatic interactive stress factors, as well as pollutant dose, in the estimation of a dose-response function. A related concern is the potential interactive effects between O_3 and acid precipitation as well as with other pollutants. Futher, current experimental designs tend to ignore the potential role of input substitutions as typically practiced under commercial production conditions. Finally, the unknown functional relationships between a given crop and a pollutant is a source of model uncertainty in estimates of the economic impact of air pollutants on agricultural productivity. The effect of these biological sources of uncertainty in yield estimates on economic analysis of air pollution impacts is unresolved but preliminary research by Adams *et al*. (1983) and Adams and McCarl (1983) suggests that for policy analysis, the level of resolution in agricultural data sets such as those generated in the NCLAN program are adequate to perform credible economic benefits assessments.

Some of these dose-response issues (e.g., water stress and other interactive processes) are being evaluated in studies of ozone effects (Heck *et al*., 1983). Also, some attempts have been made to mitigate these limitations in the context of performing meaningful economic assessments. The review of economic literature on assessing agricultural crop losses (Section 4.0) discusses some of the analytical and practical problems and solutions to these limitations in the dose-response literature.

3.0: ECONOMIC ANALYSIS OF AIR POLLUTION EFFECTS -- SOME THEORETICAL CONSIDERATIONS

3.1 Introduction

The preceding discussion focused on biological and air quality issues concerning the effects of pollutants on agriculture. Translation of such physical effects into economic effects requires some concept of what consititutes economic benefits. The definition and measurement of economic benefits thus require an understanding of the axiomatic basis of economic theory -- its assumptions as well as its strengths and weaknesses in providing meaningful economic estimates for use in environmental policy. Some key theoretical aspects associated with measuring economic benefits are discussed in this section.

Economic analysis of environmental quality is the subject of many treatises. This section only attempts to abstract the subject, drawing out essential points relevant to changes in production and consumption of agricultural commodities. The analysis of environmetal quality for regulatory purposes has at its heart the objective of implementing socially desirable controls (controls which maximize net economic benefits) on those who alter environmental quality. However, the criteria for "socially desirable" are less than clear. Society involves many individuals and groups with diverse and often conflicting opinions and preferences. Controls may and most often do affect the welfare of these individuals or groups differentially. Virtually any statement on economic benefits involves a value judgment as to whether the benefits summed across some parts of society outweigh the costs to other parts of society.

3.2 Criteria for Judging Social Desirability

Four criteria have been proposed for making such judgments. The first is the Pareto criterion which states that an environmental policy or action is socially desirable as long as the resultant welfare of every member of society is improved or not made worse. However, the Pareto criterion is rarely satisfied, and other criteria have arisen.

Two prominent criteria are the Kaldor (1939) and Hicks (1941) compensation criteria. The Kaldor criterion states that an environmental action is desirable as long as there is the potential for Pareto improvement, i.e., as long as the gainers receive more than the losers, then the gainers can hypothetically compensate the losers, thereby improving the welfare of all. The Hicks criterion takes the opposite but highly related viewpoint that a socially desirable situation is achieved when the losers cannot bribe the gainers into not undertaking the action. The main difference between the Kaldor-Hicks compensation criteria and the Pareto principal is that, unlike the Pafeto criterion, the Kaldor-Hicks criteria do not impose differential welfare weights for individuals (if one individual is adversely affected, then an action is not socially desirable). A fourth measure states that an action is socially desirable as long as the differentially weighted sum of the welfare of individuals with the action is greater than a similarly weighted sum without the action (Harberger).

3.3 Measures of Welfare

The criteria for judging socially desirable changes in environmental quality require measures of welfare. The economically accepted measures of welfare are compensating and equivalent variation as reflected in economic surplus measured through consumers' and producers' surplus [see Just, Hueth, and Schmitz (1982) for definition and more extensive discussions].

Consumers' and producers' surplus are measures which, in some cases, represent the utility gained by individuals when: (1) in consuming goods, they obtain goods at a price less than the maximum they would be willing to pay; and (b) in producing goods, they sell at a price above the price at which they would have been willing to supply. The surpluses are portrayed for a simple single commodity market in equilibrium in Figure 3.1.

Within Figure 3-1, the curve DD gives a representative demand schedule (prices which the aggregate of consumers would pay to obtain a given quantity of the commodity). The curve SS gives the supply schedule (prices the aggregate of producers would require to provide a given quantity of the commodity). In this setting, the market equilibrium would be at P*,Q*. Consumers' surplus (CS) in this case is the area above the price line (horizontal at P*) but below the demand schedule (DD), while producers' surplus (PS) is the area above the supply schedule (SS) but below the price line.

3.3.1 Consumers' Surplus

Consumers' surplus, as mentioned above, is defined geometrically as the area CS. The concept underlying this geometric calculation originated with Dupuit (1849) and was formalized by Marshall (1920) who defined consumer surplus as "the excess of the price which he would be willing to pay for the thing rather than go without it, over that which he actually does pay --." According to Marshall, the area under a commodity's demand curve is the consumer surplus. However, if such a demand area assumes that income and other prices remain constant, real income will increase if the price of this commodity fell, increasing the consumer's willingness to pay for this and other goods. Thus, in the Marshallian context, consumer surplus can only be applied directly to those goods or groups of goods which make up a very small part of the consumer's total income. This limitation was partially addressed by Hicks, who generalized the concept to a broader range of items by allowing for income effects through the introduction of compensated demand curves which adjust for changes in real income and hence keep real incomes constant.

To understand why this area imparts any measure of welfare, assume an individual consumes goods to derive utility. While utility is difficult to measure, individuals are assumed to reflect the value or utility they place on a good in making tradeoffs in their consumption of goods and services. Adopting this premise, the individual's demand schedule is then the collection

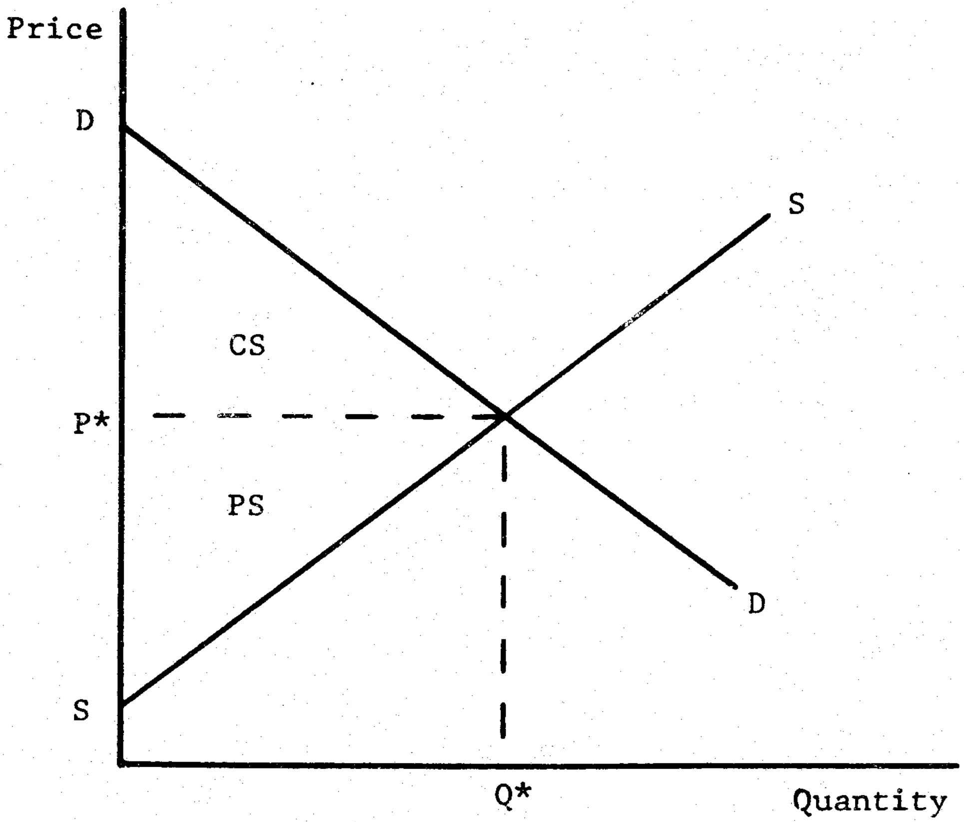

Figure 3-1. Consumers' and producers' surplus.

of price-quantity points representing the marginal utility of consumption (equaling the price) of a given quantity of goods to the consumer (Harberger, 1971). Thus, when the individual consumes goods (Figure 3-2) at price P*, then the total utility (or a measure of welfare) that an individual would gain from this consumption process is the sum of the satisfaction from consuming the first unit of good at this lower price (a_1) plus the second (a_2), etc. This sum equals the integral of the area under the demand curve from zero to Q* less the total amount paid (i.e., P*Q*).

Aggregate consumers' surplus is defined in an analogous manner. In theory, the aggregate demand function is simply the horizontal sum of the individual demand functions. The area under the aggregate demand function is the summation of the individual consumer's surpluses and constitutes a measure of aggregate welfare. Acceptance of this statement requires that one is interested in a measure of welfare in which the welfare to individuals is summed without regard to the individuals to whom the welfare change accrues (Harberger, 1971).

3.3.2 Producers' Surplus

Producers' surplus, as mentioned above, is the excess that producers receive over the minimum price at which a seller is induced to part with a good. The minimum price at which a seller is "induced" is given in theory by the supply curve and is the value of that unit to the seller (Harberger, 1971). Figure 3-3 portrays such a situation. Here, producers' surplus is the area between the price line and the supply curve. Equivalently, producers' surplus is the equilibrium price (assuming that increases in price are not due to technological externalities) times the equilibrium quantity (total revenue) minus the area under the supply curve from zero to the equilibrium quantity (which theoretically equals total cost).

Producers' surplus is not as readily accepted in a welfare context as is consumers' surplus. The reasons for this are two-fold. First, there has been conceptual as well as pragmatic discussion over whether economic rent or profit is a more meaningful term for this quantity. Second, there has been controversy over whether the concept has any meaning, or more correctly to whom the surplus accrues.

Mishan (1968) states that economic rent provides "a money measure of the welfare change arising from a movement of factor prices in exactly the same way that consumer's surplus provides a money measure of the welfare change arising from a movement in product prices." Mishan further states that the quantity called producers' surplus above is, in fact, more properly economic rent, arguing that this quantity, when it exists, is an imputed rent to the factors of production. Thus, producers' surplus and economic rent are argued to be conceptually analogous. On the other hand, while Just et al. (1982) use economic rent, they also show that individual producers' surplus is the sum of rents to all producers below that individual in the vertical chain plus the ultimate (final) producers' surplus.

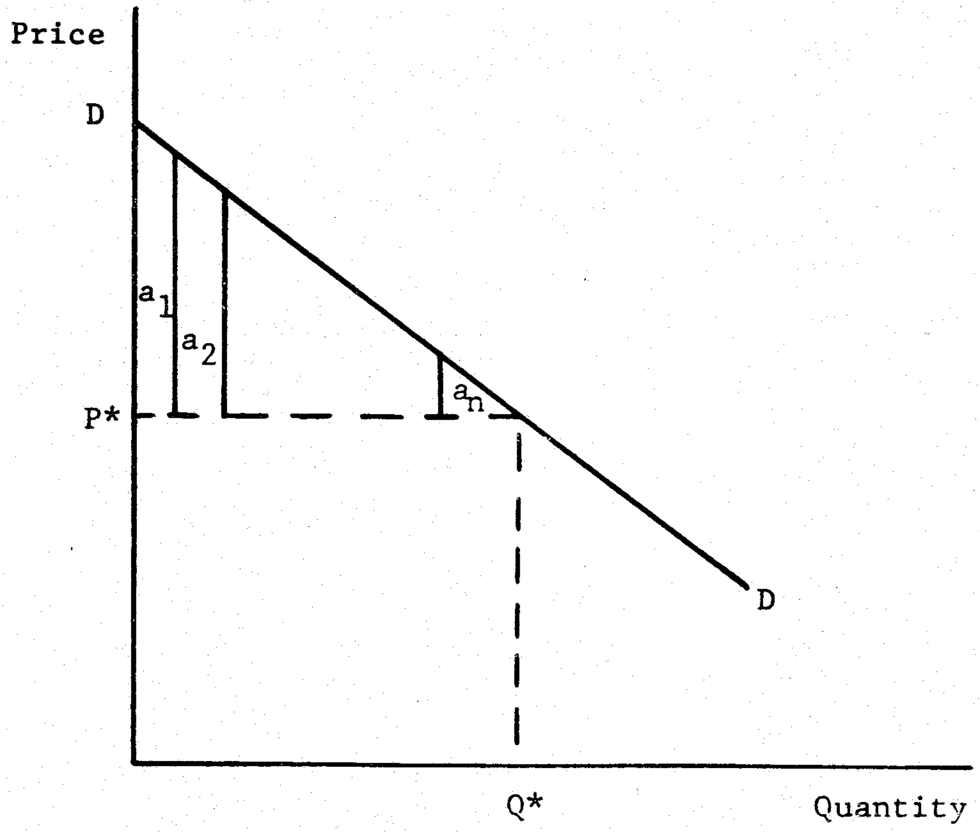

Figure 3-2. Generation of consumers' surplus.

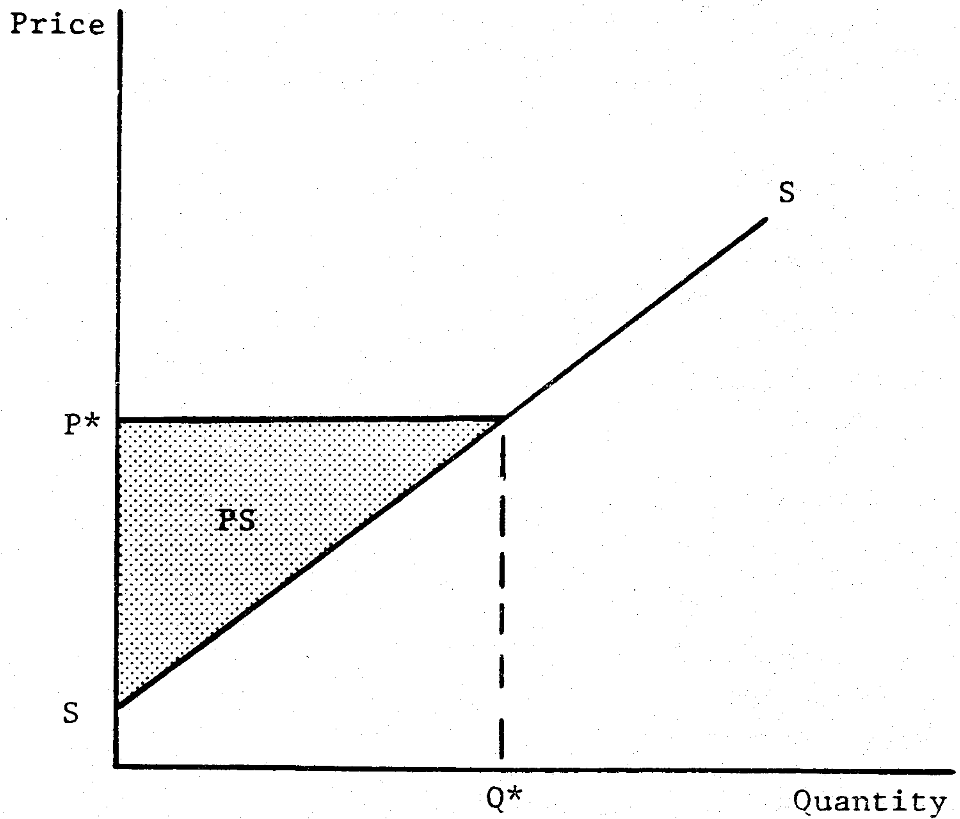

Figure 3-3. Producers' surplus.

3.4 Developing Welfare Measures for Environmental Quality Changes

Consumers' and producers' surplus cannot usually be measured directly in terms of either demand for environmental quality or demand for the results of an environmental action (e.g., better visibility or higher quality air). Where environmental quality changes are reflected in markets, such as increased agricultural production from improved air quality, direct measurement of economic surplus is possible. However, for many environmental commodities, the welfare impact (the change in economic surplus) of an action indirectly through related or contingent markets must be measured. These contingent markets can provide estimates of consumer "willingness to pay" for environmental change, in a sense tracing out a demand curve for the non-marketable good.

The emphasis in this discussion is on those environmental policies or actions which affect production of marketed commodities. Hence, the following development deals with the measurement of economic surplus or welfare through shifts in well ordered markets. The topic of non-marketed goods is addressed subsequently in terms of some general issues surrounding development of contingent market values.

3.4.1 Measuring Welfare Changes Under Alternative Actions

Direct measurement of economic benefits (economic surplus) associated with alternative environmental policies is relatively straightforward when well-defined markets exist. However, even in this case, the environmental action may result in a wide range of possible measurement situations concerning changes in supply and demand. Applications to empirical issues require a set of operational assumptions to make the problem tractable. The use of these conceptual approaches is detailed below for actions or cases likely to arise in the case of agriculture.

3.4.1.1 Change in the supply of output because of pollution control

The effect of an environmental quality change, such as reduced air pollution on agriculture, may be an increase in yields and hence production or supply. Given an estimate of the change in the supply schedule because of air pollution, the change in producers' surplus can be computed by considering the area above the supply curve but below the price line before and after the change in environmental quality. The social benefits obtained from any changes in the consumers' surplus associated with the demand curve also need to be considered.

This situation is illustrated by the curve in Figure 3-4 where DD is the demand curve for the product, SS is the supply curve before the change, and S'S' is the supply curve after the action or change. In this case, consumer welfare before the action is given by the area labeled a; producers' welfare is given by areas labeled b plus the area labeled e. After the change, consumers' welfare increases by the areas labeled b + c + d, and producer welfare is reduced by area b but increases by area f + g, thus, the net change in producers' welfare is f + g - b, and the net increase in the social welfare

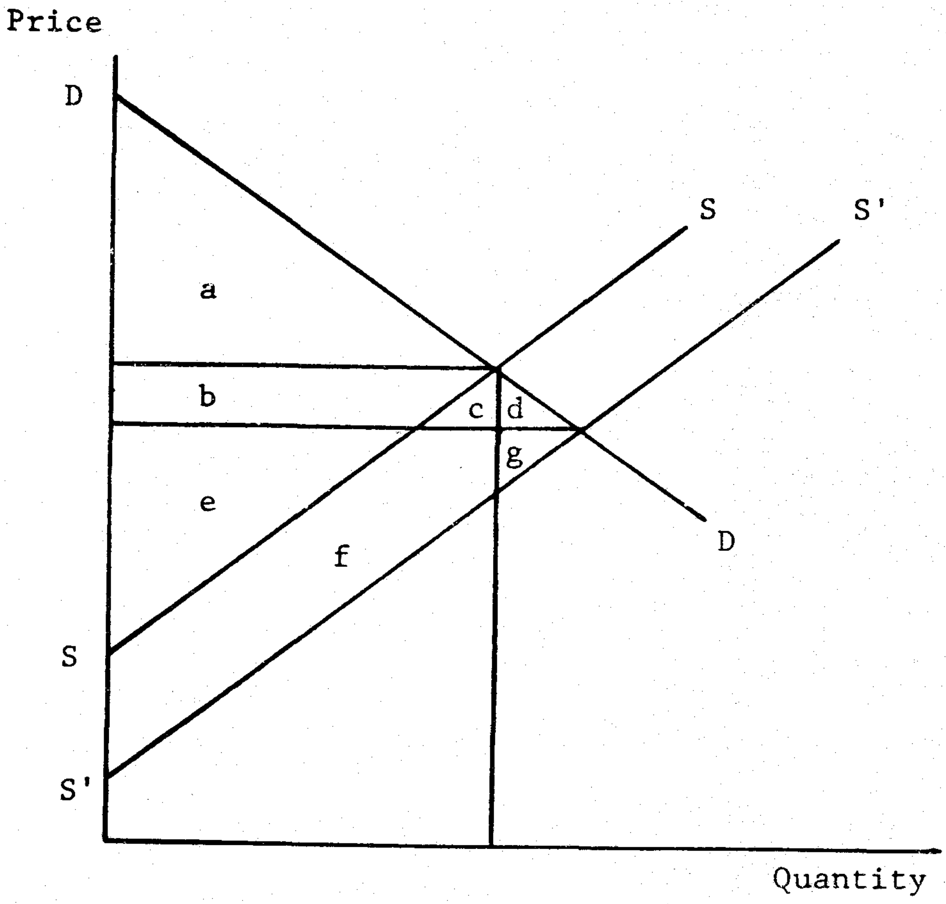

Figure 3-4. Welfare change measured in an output market.

is f + c + d + g (this diagram suggests that given a demand curve with an elasticity other than infinity, it is unclear whether producers gain or lose from the introduction of an environmental change).

3.4.1.2 Estimate of change in total profits

Estimates of changes in profits are measures of producers' surplus or economic rent. Thus, a change in profits with a change in environmental quality is a welfare estimate of the change in the producer's position because of the change in environmental quality. However, an assumption needs to be added for this to be an adequate welfare measure. That assumption is one of a perfectly elastic demand curve. Under a perfectly elastic demand curve, the change in profits from a supply shift will be a change in producer welfare. Thus, this estimate can be used as a total benefit measure when one assumes the action does not influence demand prices.

This situation is illustrated graphically in Figure 3-5. Here, the supply curve before the environmental action is assumed to be SS. The supply curve after the action is assumed to be S'S'. The total willingness to pay before the action is the area above the curve SS and below the curve DD which in this case is equivalent to producers' surplus or profits before the action. After the action, the total welfare is the area below DD but above S'S' which is profits after the action. The shift in profits in the before and after situation is the shaded areas in Figure 3-5. Since with a perfectly elastic demand curve consumers' surplus is zero, only the change in producers' surplus or profits is relevant in developing a total benefit estimate.

3.4.1.3 Estimates of a change in total cost

The change in total cost required to deliver a quantity of output can be utilized as a measure of the change in total social welfare -- consumers' plus producers' surplus, when society is assumed to have a perfectly inelastic (i.e., fixed quantity) demand curve for a good. Total consumers' plus producers' surplus is defined as the area under the demand curve, but above the supply curve. Total cost is the area under the supply curve. Thus, when there is a shift in the total cost of providing a good, this change in cost can be equated to the change in consumers' plus producers' surplus.

This situation is illustrated graphically in Figure 3-6. Here, the supply curve before the action is assumed to be SS; the supply curve after the project is assumed to be S'S'. The area below the supply curve SS up to the quantity sold as defined by the demand curve DD is the cost of producing this good. The cost after the action is the area below S'S' and up to the demand curve DD. Consumers' plus producers' surplus can be equated to this change in total costs under these conditions, and the shaded area gives a change in total costs.

3.4.1.4 Shift in factor demand

Given an estimate of the shift in the demand curve for factors, welfare may be measured by calculating the change in the area under the curve at the intersection with the supply curve. This will involve determination of the change in the quantity of factors used and the change in the price of the

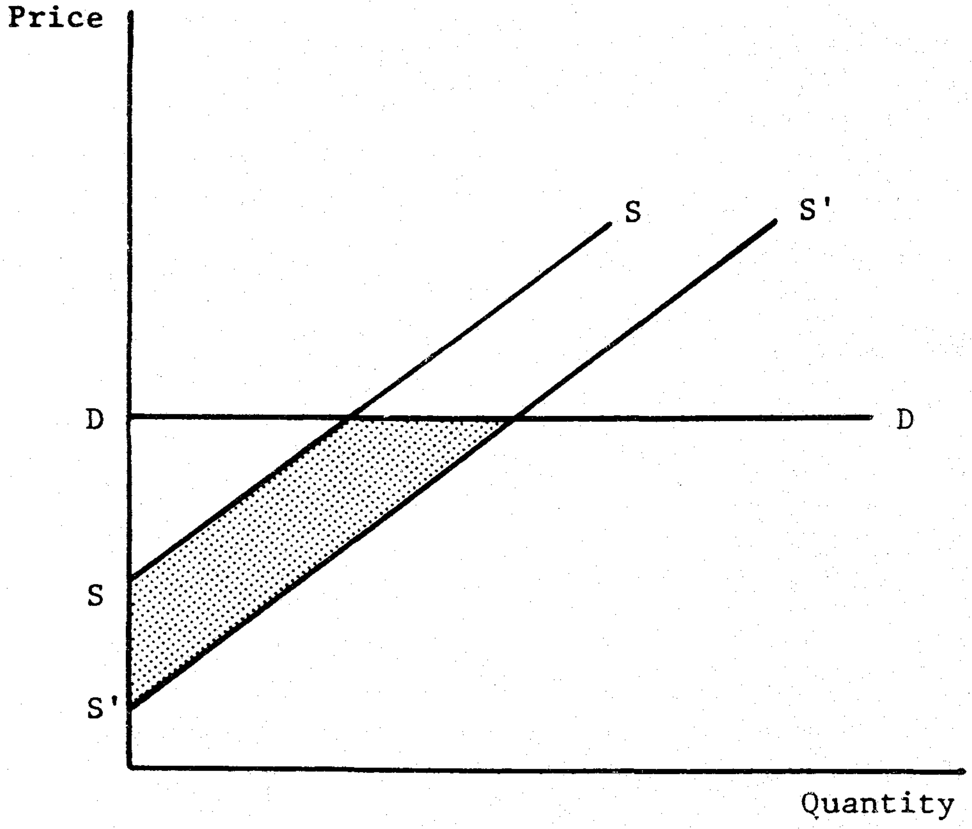

Figure 3-5. Economic surplus under perfectly elastic demand.

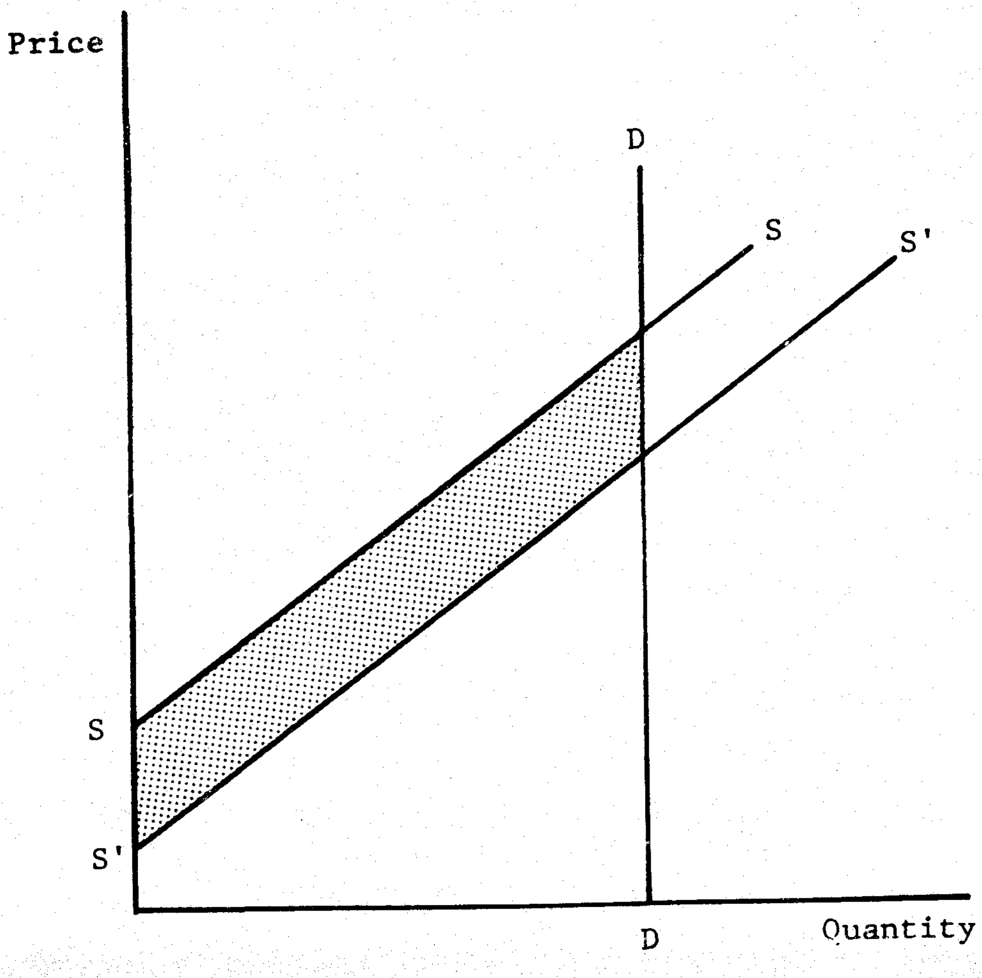

Figure 3-6. Welfare change measured through total cost change.

factors used. An approximation of consumers' surplus can be constructed by multiplying the change in price times the average quantity consumed of the factor. Special cases of this may be considered by looking at either totally inelastic factor supply or totally elastic factor supply. Changes to the rents going to factor owners, as well as the changes in the rents to producers would need to be calculated.

This is illustrated in Figure 3-7 in which SS is the supply curve of factors; DD is the demand curve for factors before an environmental change; and D'D' is the demand curve for factors after the change. In this case, before change consumers' surplus (which equals ultimate consumers' surplus value added in the production process) equals a + b and producers' surplus equals c; after the change, producers' surplus (or the returns to factor owners) equals b + c + e, whereas consumers' surplus, or the return to the producer plus consumer surplus further up the line, equals a + d. The net effect of the action is a gain in total welfare of an area amounting to d + e.

3.4.1.5 Estimate of a change in welfare with a change in yield

In measuring economic effects to agriculture, one procedure to estimate the change in welfare has been to take the price times the change in yield before and after an environmental action. This is a form of a profit approach. However, it assumes that the demand curve is totally elastic and that the supply curve is totally inelastic. This is illustrated graphically in Figure 3-8, where DD is the demand curve for the product; SS is the supply curve before the project; and S'S' is the supply curve after the project. The shaded area then gives the change in total economic welfare which is the area below the demand curve and above the supply curve. This estimate of welfare excludes any measures of consumer welfare (assumes it to be zero). This estimation procedure is commonly used in assessments of dollar losses discussed in Section 4.0.

3.4.2 Avoiding Double Counting

Each of the five cases above represent alternative estimates of the welfare effects of an environmental action. Given that the cases imply different and unique welfare effects, the appraiser must be careful not to double count within a given case or situation (measuring the same benefit in more than one way). Just et al. (1982) show that consumers' surplus in a factor maket is equal to either: (a) the sum of consumers' surplus in the ultimate market for the good plus the sum of producers' quasi-rents (profits or returns to fixed factors) obtained in the intermediate markets when product prices vary with changes in output; or (b) simply the producers' profits (or returns to fixed factors) when the demand price to the producer is fixed. Thus, consumers' surplus as measured in a market is consumers' surplus at the consumption stage plus the rents to fixed factors used in transforming production into the final output. Similarly, Just et al. (1982) show that producers' surplus in a factor market equals: (a) producers' surplus in the lowest level factor market plus any rents to producers occurring in transforming the factor through the string of vertical markets leading to the particular market being analyzed; or (b) profits accruing to production when lower market prices are fixed. The implications of the statements are that measurements should not be done on an effect in both the factor and output markets,

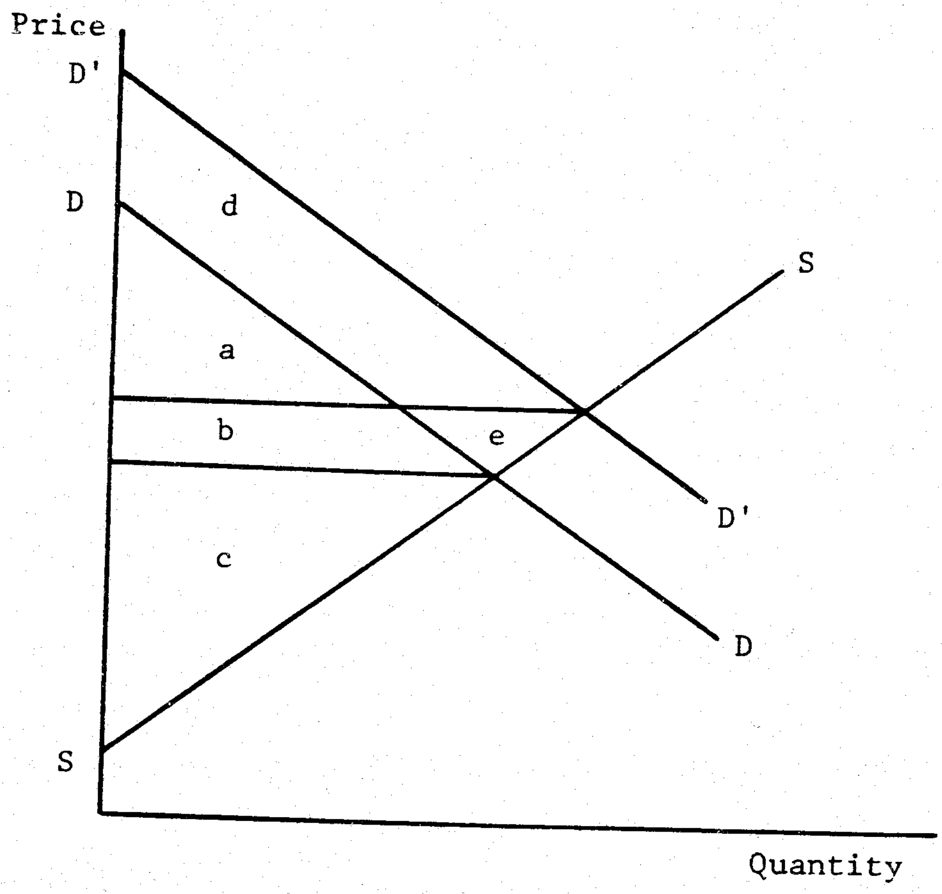

Figure 3-7. Welfare change with a shift in factor demand.

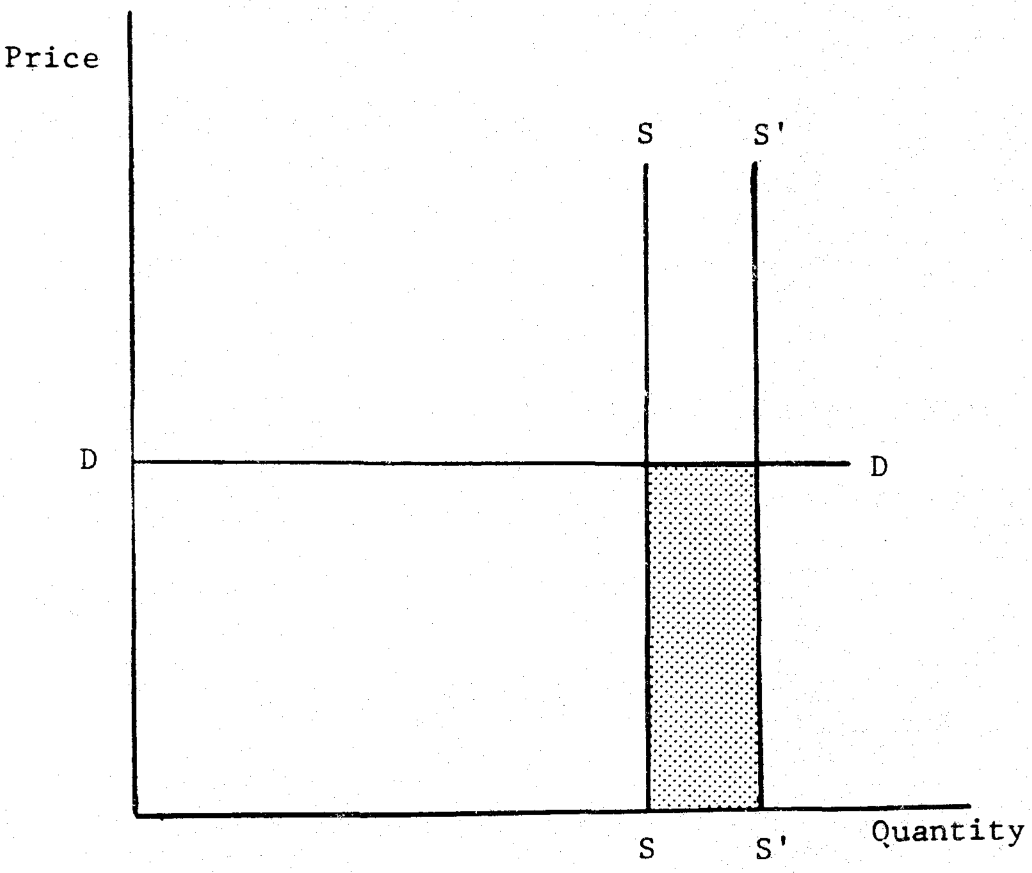

Figure 3-8. Welfare change with a change in yield.

and that the nature of the price assumptions determines the answer. Furthermore, surplus in only one of the firm's factor (assuming the factor is essential) or product markets needs to be measured.

3.4.3 Should Consumers' Surplus be Considered?

The above discussion introduces both consumers' and producers' surplus. In many environmental quality appraisals, the welfare analysis is done using only the concepts of producers' surplus (i.e., changes in producers' profits) assuming that the demand curve for the items covered by the project is perfectly elastic (i.e., fixed price). This assumption is valid only in those cases where the environmental quality change will be small enough so the demand for various items affected by the change will not be altered. However, in many cases air quality changes will be widespread, resulting in a substantial shift in production of certain items and the assumption of fixed price is implausible. In this case, consumers' surplus should be considered.

3.4.4 Induced Effects

One potential category of benefits and costs effects concerns induced (secondary) impacts. Induced impacts refer to economic effects which are stimulated by changes in the economic activity of groups of economic agents. Examples include increased economic activity within the marketing channel caused by an increase in farm production. The evaluation of such impacts and their inclusion in project appraisals has been a controversial theoretical subject. This controversy has involved discussion of secondary effects from both a national cost-benefit perspective and from a regional distributional perspective. Stoevener and Kraynick (1979) review the literature and summarize the theoretical arguments relating to national benefits, stating "Secondary effects in the region in question would be offset by effects with the opposite sign in other regions ... There are only two conditions under which secondary benefits would arise. The first deals with ... surpluses ... in ... fixed as well as variable capital stock ... The second ... involves the capacity utilization of the existing resources. The extent to which unemployed and underemployed labor resources in a potential area can be employed has emerged as a bonafide benefit ... capacity utilization of other existing resources has not received as much attention." This subject has been estimated empirically in several different settings [see Bell and Hazell (1980) or Haveman and Krutilla (1968)].

Induced effects also play a role in the analysis of regional distributional effects. Here the concept has clear applicability, although it cannot be stated unequivocally that these effects are contributions to social welfare. However, the empirical measurement of such effects can be complex, utilizing such techniques as input-output analysis, land value methods, or other types of models (Haveman and Krutilla, 1968).

3.5 Valuation Methods

The above discussion has focused on the general theoretical framework to valuation of the benefits of environmental change. Attention is now turned to the various empirical approaches which implement these theoretical concepts to valuation of benefits. The following discussion of empirical methodologies for valuing environmental commodities is general in thrust. Specific applications are found in the literature review in Section 4.0.

There are several economically consistent methods for deriving the value of alterations in the air quality environment. There are a number of important principles (following Freeman, 1979) involved in the formation of these methods.

1. The methods must yield measures of value in monetary terms.
2. The methods must be based on a "willingness to pay" concept in which one is considering the amount of income (as measured in other goods and services) individuals are willing to give up to achieve or accept environmental alterations.
3. The impacts predicted by the methods must be related to alterations in the environment and in turn related to the magnitude of alterations possibly induced by feasible air quality improvements.
4. The methods are ultimately based upon theoretical models of individual behavior and interactions among individuals.
5. The numerical measures used in implementation should correspond closely to the measures assumed in the theoretical model.
6. The method employed in a study must be selected so that it is appropriate in terms of the producer and consumer behavior and data at hand.

The methods fall into three classes: (a) development of value estimates from observed economic behavior; (b) development of value estimates from elicited responses; and (c) development of value estimates from synthesized or simulated economic behavior. Each of these classes encompasses a range of specific valuation techniques which will be discussed individually. Examples of many of the various approaches appear in Section 5.0.

3.5.1 Valuation Based on Observed Economic Behavior

Economists commonly develop estimates of effects from changes in environmental attributes by observing the ways economic behavior of different parties are affected by changes in environmental attributes. Such an approach would involve observing behavior of a number of individuals (over time or over space) obtaining data on both the economic variables of interest (prices, profits, costs, etc.) and data on those items which differ across individuals, including data on environmental quality. Using these data, an estimate is formed on the consequences of changes in environmental variables.

3.5.1.1 Profits

An estimate may be made of the change in profits via a scheme which attempts to develop estimates on firm profits as a function of environmental quality, the inputs the firm uses, the firm's input prices, the output price, the firm's output, and the alterations in these caused by an environmental action. This information may then be used: (a) to estimate a profit function following duality theory (see Varian, 1978, or Silberberg, 1978) which in turn may be used to derive input demand equations or output supply equations; or (b) simply in an accounting sense to derive estimates of changes in profits because of changes in environmental quality, all other things held constant.

3.5.1.2 Cost

Cost approaches are more common in the environmental quality literature. Basically, firms are observed to determine changes in costs encountered when producing a constant mix of goods, because of a change in environmental quality. This approach is implemented when one studies changes in maintenance costs, mitigation costs, replacement costs, or prevention costs from a change in environmental quality. Maintenance cost is a basis for a cost estimate when one believes that the effect of the environmental quality changes are manifested in the increasing costs of maintaining equipment. Mitigation costs refer to those costs incurred in overcoming the effect of the changes in environmental quality. An example of this would be an increased use of fertilizer to offset yield depression caused by a worsening in air quality. Similarly, the opportunity cost of changes in crop mix (from pollutant-sensitive to pollution-resistant) may be important. Replacement costs deal with the costs incurred when replacing assets because of their demise from changes in environmental quality. Here, one deals with the questions of either replacing the flow of services from some other, costlier source or the replacement of capacity at the affected source through capital construction. Replacement costs also can refer to so-called shadow project approaches wherein projects are constructed to replace lost production (e.g., construction of controlled atmosphere greenhouses to replace depleted production). The final category of costs is prevention costs. Here, one would account for costs which were incurred in preventing the effects of changes in environmental quality. Such costs include, for example, switching to resistant cultivars of the same crop to minimize the cost of a degradation in air quality.

Another cost approach which could be used is to estimate the dual cost function using the amount of output as an argument in the function, then differentiating in a duality context to obtain the change in the supply of output and demand for input schedules as discussed under the marginal cost section below. All of these cost approaches are founded on the assumption that the same level of demand is to be supplied before and after the controls and the resultant change in environmental quality. Further, one should value only the change in environmental quality caused by the environmental change when doing an assessment.

3.5.1.3 Marginal costs of output

Observed behavior may also be manipulated so one obtains estimates of changes in the marginal cost of producing output. Here, the basic approaches are identical to those used for cost above, when one concentrates on the marginal changes caused by environmental change rather than a total cost estimate. Again, this may be derived through either a cost function or a profit type approach. Also, estimates may be obtained assuming that demand is inelastic and that factor supply prices are elastic. Then the total change in cost incurred by a change in environmental quality may be divided by the product being sold and this used as the incremental marginal cost of altered air quality.

3.5.1.4 Factor demands

Observed economic behavior may be used to generate estimates of changes in the price a firm is willing to pay for factors with and without the environmental policy or action. This is commonly done in environmental economics using the hedonic approach in which land values are estimated as a function of a number of parameters including environmental quality. Subsequently, the land values are differentiated with respect to environmental quality to obtain an implicit price for changes in environmental quality (see Freeman, 1979, for details). This procedure may also be done informally by examining two situations where all factors except environmental quality are assumed constant and then dividing the difference in land price by the change in environmental quality to get the marginal effect on the factor price of the change in environmental quality.

The analysis may also be done with schedules either from directly estimated demand and supply equations for factors, or from derived demand or supply equations derived through either profit or cost function estimation. Given these schedules, one may simply calculate the relevant producers' and consumers' surplus. Whether the base data exhibit price changes within the output market needs to be examined to determine whether producers' and consumers' surplus are being estimated or, similarly, whether the price of factors are allowed to change when looking at the output price. If so, a consumers' and producers' surplus estimate is generated. If not, then just a producers' surplus estimate is generated, raising the question as to whether to go on and examine the consumers' surplus by looking at the area under the demand curve and above the price line. Estimates directly obtained from the profit function will not yield consumers' plus producers' surplus; rather, the output supply or input demand equations as a profit function as estimated with the prices of the inputs and outputs implicit in it must be estimated directly.

3.5.2 Valuation Based on Elicited Responses

A fundamentally different approach to valuation can be carried out based on data directly elicited relative to environmental attribute changes. This type of data is commonly called nonmarket data and refers to data obtained through surveys, questionnaires, bidding games, and voting. Examples of these types of questions in an environmental action would involve the willingness of individuals to pay for increased visibility, or the willingness of individuals to pay for retained future plant species which are being depleted by air pollution. This particular technique, while important in the overall economics of environmental improvement, may not be that important in assessing benefits of air quality actions on agriculture. Thus, we only provide an overview [Freeman (1979) provides a much more comprehensive discussion].

The basic approach is directed toward the development of benefit estimates for changes in environmental attributes using elicited data. The data development process involves several approaches. First, one can ask individuals to state their willingness to pay to obtain some specified level of change in the environmental attribute. This particular type of question may take the form of: "How much would you be willing to pay for a 20 percent improvement in visibility in this air basin?" Alternatively, individuals could be asked how much of a change in the environmental quality attribute they would demand at a certain price.

There are a number of difficulties regarding developing demand equations from this kind of data. The first is that the way questions are asked can lead to biased responses. The second is that it may be very difficult to provide incentives to obtain accurate behavior. Bias in the answers that are obtained may arise because of the public good nature of environmental quality [see Freeman (1979) for elaboration on this point]. Inaccuracy in responses may also occur because individuals may not fully understand the questions or may have no judgmental basis for making an accurate decision [again, Freeman (1979) discusses this point].

3.5.3 Value Estimated from Simulated Economic Behavior

It is often difficult to observe situations in which all factors can be held constant or controlled other than environmental quality. Consequently, a valuation technique increasingly used in appraisal of certain environmental actions is based on a synthesized economic model of the situation involved. The economic model may be very formal, using such things as mathematical programming (see Smith and Brown, 1982; Adams *et al*., 1982), simulation, econometric procedures (see Manuel *et al*., 1981), or optimal control (Burt, 1981). Alternatively, the work may be done using budgeting in which a change in yield is traced through a simple deductive budgeting process to develop estimates of the changes in profits (Kopp and Vaughan, 1983). The specific modeling techniques are described in detail elsewhere. Here, we will only review some of the assumptions.

The assumptions of any model fall into two major classes. First, there are assumptions leading to the exact structure of the models, i.e., identification of the relevant and irrelevant variables, the conceptualization of the factors which change or do not change with changes in environmental quality, etc. Second, there are assumptions involved with the model solution process. For example, in a budgeting exercise, one may assume acreage to remain unchanged, thus price times change in yield gives total change in firm revenue, or the more detailed assumptions of additivity, divisability, certainty, and continuity used in a linear programming exercise. Synthesized approaches have been done in terms of changes in profit, changes in costs, and even changes in schedules of demand or supply as discussed above. An important advantage of modeling is the ability to systematically alter the environmental attributes assumed to occur because of a potential action. This allows the models to forecast effects of, say, a different secondary ambient air quality standard before such a standard is actually implemented.

3.6 Final Comment

The theoretical and methodological measures of economic benefits discussed here provide one means of judging the efficiency of alternative environmental states. Policy decisions, however, tend to be guided a least as heavily by equity matters or in response to some more complex political calculus. Nonetheless, environmental benefits assessments need to be structured in accordance with accepted economic principles and practices, if only to ensure a common measure of benefits across assessments.

The assessment methodologies available to the economist draw their legitimacy from economic theory. Implementing these procedures or methodologies involves issues of a more practical or applied nature, including an appreciation for the mathematical/statistical estimation techniques which underly the procedures. As with any exercise in applied economics, performing defensible, credible assessments requires additional skills and abilities beyond application of pure theory. In ecosystem assessments, a working knowledge of basic physical/biological phenomena may be needed to both cast the problem in a tractable format as well as to interpret the plausibility of the results. Some of these economic and physical/biological issues that are important to an air pollution assessment are discussed in Sections 4.0 and 5.0.

4.0: A REVIEW OF THE AIR POLLUTION CONTROL BENEFITS LITERATURE

4.1 Introduction

In view of the importance of U.S. agriculture to both domestic and world consumption of food and fiber, major reductions in supply because of air pollution could have a substantial effect on human welfare. Purely biological research, as discussed in Section 2.0, indicates that crop yields may be substantially reduced under current ambient air quality conditions. The possibility of such reductions has resulted in numerous attempts to assess dollar losses caused by ambient ozone and other pollutants (or the benefits of pollution control). The resulting dollar-loss estimates from these studies, their validity, and implications for oxidant control policies are discussed in this section.

4.2 Assessing Air Pollution Control Benefits: Economic and Other Issues

Before beginning a review of the existing assessment literature, it is worthwhile to review some relevant issues which could be addressed within the literature. How well these issues are addressed is one criterion by which the adequacy of the assessment literature can be judged. Because of the economic orientation of this document, the concentration is primarily on economic issues, with limited attention devoted to technical issues relevant to the benefit valuation of improved air quality.

4.2.1 Economic Aspects

There are numerous issues to consider when examining air pollution-induced vegetation or ecosystem damages. The discussion below first focuses on the more aggregate or macro issues and then works toward microeconomic issues. This ordering does not imply importance or relative contribution to the validity of resultant economic estimates. Ultimately, it is an empirical question as to which issues are most relevant in a given benefits assessment.

4.2.1.1 Welfare

Fundamentally, all decision making related to the formulation of public policy centers on perceived changes in "public welfare." As noted in Section 3.0, there are alternative criteria by which to judge changes in public welfare arising from policy actions. Typically, in the benefit-cost analysis of air pollution control strategies, or any other environmental regulatory policy decisions, regulatory actions do not lead to "Pareto Optimal" results (i.e., a regulation from which all parties benefit). Virtually any air pollution control action or regulation will disadvantage someone (polluters, consumers, agricultural producers) in terms of their perceived welfare. Also, there is a problem in quantitative definition of welfare. A measurable basis for comparison is needed so alternatives may be judged against one another.

This implies the need for common or consistent measures of value for the various welfare components. The demand function for many potential dimensions of welfare, however, is not often revealed or known in practice (e.g., environmental quality, change in nutritional status, change in aggregate farm income, or change in consumer price index).

Thus, several issues arise in the valuation of benefits associated with improved air quality: 1) What are the appropriate dimensions (interpersonally, regionally, functionally) of welfare? 2) How should these welfare characteristics be measured? 3) How should (or can) they be weighed across recipient classes? 4) For those impacts which involve non-market environmental commodities, how should welfare effects be formed to permit informed decision making? 5) Who makes the decision -- what welfare items are relevant to them? All of these issues or questions affect the measurement of welfare benefits and costs associated with various air pollution control strategies.

4.2.1.2 Distributional Concerns

The effect of air pollution on a given plant reflects natural or physiological processes associated with the toxin in question. However, the varying economic impacts of air pollution on agricultural producers may be a function of such factors as: 1) edaphic factors and endowments; 2) production systems and alternatives; 3) geographical location; 4) types of agricultural crops planted; 5) availability of substitute crops; and 6) managerial ability. Consumers of these agricultural products can be classified into strata or groups based upon such factors as: 1) income level; 2) regional location; 3) percentage of income spent on food; and 4) food and other preferences. If "Pareto Optimal" decisions cannot be made (as alluded to above), some consumer groups within these strata or producers will be relatively advantaged by a given regulatory decision. Further, the distribution of impacts will change over time. Several distributional issues which arise in an assessment of air pollution policies include:

1. How are gains and/or losses distributed between various classes of people (for example, tradeoffs between consumers and producers)?

2. How are gains and/or losses distributed regionally, commodity-wise, or among factor owners?

3. What might be the impact of an action in terms of strata within a class (e.g., farm size or income distribution)?

4. How do the distributional effects change with time?

The use of techniques in assessment of air pollution control strategies which ignore or are incapable of addressing distributional consequences will result in misleading estimates whenever: (1) prices in the output or input markets in the agricultural sector are sensitive to changes in yield and input usage from varying levels of air quality; and (2) producers and consumers adopt different means for adjusting to changes in air quality.

In the first case, if the percentage yield increases caused by air quality improvements are less than the consequent percentage price reductions, an assessment that ignored such price effects would attribute benefits to the producer when in reality there would be producer losses (and consumer gains). The second concern relates to producer (or consumer) adaptation strategies. For example, if producers can adopt different production patterns (or utilize more resistant cultivars or adopt other compensatory input changes such as to add lime and fertilizer) and thereby reduce potential losses (or increase gains) they may suffer from an air pollution increase, they will do so. Failure to account for this adaptive producer behavior will result in overestimates of losses experienced by producers in the face of air quality degradation or underestimates of the gains incurred from changes in pollution levels. Similarly, consumers may substitute certain agricultural commodities in the face of relative price changes, so that the net effect of a rise in the price of a commodity because of air pollution-induced supply changes may not be as severe as first indicated.

4.2.2 Biological and Practical Issues

The need for plant response information measured in terms of yield rather than injury has been noted by most economists doing assessment research (e.g., Leung et al., 1978; Adams and Crocker, 1982a). Some plant scientists have also recognized the need to report response in terms of yield if economic losses are eventually to be estimated. For example, Oshima and coworkers (Oshima, 1973; Oshima et al., 1976; Oshima and Gallavan, 1980) have done extensive work to develop methods for evaluating and reporting crop losses in terms of potential or actual yield reduction. Continuous air monitoring, chamber exposures, and monitoring of plant species are combined in a comprehensive method for determining yield reductions. Oshima's dose-response function for alfalfa has been used as the basis for several estimates of the dollar loss from ozone exposure. The recent work arising from NCLAN (Heck et al., 1982) also provides response information in a readily usable form for economic assessments. Preliminary NCLAN response studies have been used to derive some of the loss estimates reported subsequently in this section and serve as the primary data source for ongoing assessments.

Biological data, such as yield response functions, are important inputs to economic assessments of vegetation damages. In the absence of site or regional specific response functions, economists and other assessors needing such data must either extrapolate from existing reponse functions from the plant science literature or estimate these relationships directly from secondary data on production and air quality. The credibility of these extrapolation or estimation procedures and their implications in terms of the resultant economic loss estimates is ill defined. Thus, the biological and air quality data used in economic assessments must also be recognized as a potential source of uncertainty in resulting dollar loss estimates.

As the subsequent literature review will reveal, past attempts to assess the benefits of pollution control to vegetation have led to highly divergent loss estimates. In addition to the role that different economic assumptions and methodologies may play in loss estimates, such divergences may also be attributable to some specific biological and air quality data issues or problems:

1. The effect of sparse data on oxidant-induced crop losses. The lack of such data has caused assessments to be based on extrapolations from available foliar injury estimates to obtain often unreliable yield reduction estimates.

2. Selection of the most appropriate mix of crops and cultivars, regions, and time periods in the analysis. Crop prices, production levels, and ozone exposure vary geographically and temporally, with resultant changes in dollar loss estimates.

3. Selection or definition of the background ambient levels to portray "clean air" (absence of ozone) in the analysis. When used in combination with a standardized dose-response function, the use of different background levels provides different yield reduction estimates and ultimately different dollar losses.

4. The difficulty of extrapolating from controlled chamber experiments to agronomic regions with all the required assumptions regarding soil type, precipitation regions, oxidant exposure patterns, solar radiation levels, and interactions among these edaphic and climatic variables.

It is not possible to sort out the relative contribution of better economic methodologies vis-a-vis better technical data to assessments of environmental regulation. However, recent empirical work of Adams _et al_. (1982) suggests that adequate economic representation may contribute as much as biological data to the measure of net benefits. For the particular circumstances Adams _et al_. (1982) studied, price responses and producer adaptations play an equal role in determining the predicted supply or production adjustments resulting from an air quality improvement (equal to the biological predictions of yield changes triggering the economic reactions). In their analysis, the ultimate production effects and consequent benefits estimates of air pollution hinge as much on an adequate representation of producer and consumer decision processes as they did upon the magnitude of the yield response functions. The implication of this observation is that both representative _biological_ and _economic_ responses are important in performing economic assessments.

4.3 Economic Assessment Methodologies Applied to Agriculture

Air pollution-agricultural assessments found in the literature fall within three methodological categories. As discussed in Section 3.0, discrimination among these various assessment types is required, as their informational content and economic validity can differ markedly. The first type uses damage functions to report crop losses in physical units such as the reduction in actual or potential crop production in a given geographical unit (e.g., a state or region). Examples include the recent work by Loucks and Armentano (1982) and the "DAMAGE" model defined in Moskowitz _et al_. (1982). This type of assessment is not discussed further in this section as they make no claim to report economic losses. The second (and most prevalent type of assessment of those reporting dollar losses) translates the physical losses obtained from damage functions into a dollar value by multiplying estimated yield losses by an assumed constant crop price. For the purposes of this section, this approach is defined as the "traditional" procedure. As an economic assessment methodology, it suffers from serious conceptual weaknesses which limits the validity of the estimates to some very restrictive cases, as elaborated in Section 2 above under the case 7 methodology. Thus, while economic theory presupposes that value can be expressed in monetary terms, dollar loss estimates obtained from this traditional approach should not necessarily be viewed as economic estimates. The third assessment type features the use of theoretically justified economic methodologies and hence may be viewed as economically consistent assessments. Such studies provide estimates of benefits of control in dollar terms which account for producer-consumer decision-making processes and hence distributional consequences of alternative environmental states. These estimates will more accurately reflect the real economic costs of air pollution for those situations where economic processes and markets are known to operate as in the case of agricultural production. Dollar loss estimates arising from the traditional and economic assessment methodologies are seldom distinguished in the popular press. However, economists generally discount the monetary estimates obtained from the "traditional" or damage function type of assessment [critiques of this approach may be found in Leung et al. (1978) and Crocker, (1982)].

The advantage of the traditional procedure is the relative ease with which dollar values may be obtained. More comprehensive economic assessments, as exemplified by Leung et al. (1982), Benson et al. (1982), Adams et al. (1982), Dixon et al. (1983), and Adams and McCarl (1983) attempt to account for market impacts of air pollution-induced yield reductions and producer behavioral responses. These studies use somewhat different techniques as determined by the structure of the particular economic problem (i.e., duality, mathematical programming, econometric). However, they all explicitly deal either with price adjustments, providing estimates of the economic losses to various economic agents, such as producers and consumers or both. In the Benson et al. (1982) and Adams et al. (1982) studies, the results obtained from these comprehensive economic analyses were compared with estimates obtained from the same data using the traditional procedure. The differences were moderate to large, with the traditional procedure overestimating losses from air pollution when moving from a "clean air" to ambient ozone condition (an environmental degradation). The specific magnitude of these differences is reported in Section 5.3. A detailed review of alternative economic techniques and their suitability to environmental economic assessments is presented in Freeman (1979).

An important policy issue in benefit assessments is the need to define an appropriate welfare measure of benefits or losses to society resulting from pollution. The theoretical discussion in Section 3.0 suggests that concepts of economic surplus are appropriate welfare measures with which to compare societal benefits for policy options under restrictive assumptions (e.g., see Mishan, 1968, 1971; Willig, 1976; Just et al., 1982). Following this reasoning, most economic assessments of policy issues now measure losses in terms of economic surplus accruing to consumers' and producers', the difference between the total amount consumers would be willing to pay (or producers would be willing to accept) for a given quantity of a commodity and the amount they actually pay (accept). As noted earlier, the traditional procedure provides estimates which at best can only address producers' effects with no attention paid to the fate of consumers'. Thus, conceptually and empirically there is a fundamental difference between losses measured by the traditional procedure and those obtained from more comprehensive economic assessments.

4.4 Regional Loss Estimates

Most of the economic assessments in the literature focus on regional losses. This emphasis on regional effects may be attributed to the relative abundance of data on crop response and air quality for selected regions, as well as the national importance of some agricultural regions (such as the Corn Belt and California). While regional estimates are not sufficient for evaluating alternative national air pollution standards, such studies can provide useful comparative information on alternative economic methodologies for assessing environmental damages. Also, regional loss estimates may be indicative of the potential magnitudes of national losses, if that region (e.g., the Corn Belt) produces a dominant share of major commodities such as corn and soybeans. Finally, regional studies can measure the effects of pollution on the regional economy. Economic estimates of pollution effects for selected regions are presented in Table 4.1.

Of the regional studies reported in the literature, several have focused on southern California, a region with both high pollution (oxidant) levels and an important agricultural economy. Adams et al. (1982) assessed the impact of ozone on 14 annual vegetable and field crops in four agricultural subregions of central and southern California for 1976 using a price-endogenous quadratic-programming approach. Their model solution predicted the effects of changed ozone levels on the welfare of producers and consumers. The study encompassed both ozone-induced reductions in yield and a system of linear demand functions for the study crops. Therefore, their results give information on the consequences of output price increases caused by pollution-induced reductions in crop yields. A lack of yield response functions for most crops required some rather heroic extrapolations. Specifically, ozone-induced reductions in yield were derived for most crops from the Larsen-Heck foliar injury models (1976). The authors then invoked Millecan's (1971) "rule of thumb" to translate percentage undamaged foliage to percentage yield increases for the study crops. The Oshima model (1976) was used for tomatoes and cotton. The model was calibrated against 1976 production data to confirm the model's accuracy. The authors then estimated what crop production and price would have been in 1976 if the the federal secondary ambient air quality standard (0.08 ppm not to be exceeded more than once a year) had been achieved.

The estimated losses from air pollution were found to be relatively small when compared with total agricultural value in the region -- $45.2 million when the four sub-regions were combined and $43.6 milllion when regions were analyzed separately. For all regions combined, elimination of 1976 oxidant pollution would have increased 1976 producer quasi-rents by $35.1 million and ordinary consumer surplus by $10.1 million. By way of comparison, Adams et al. applied the traditional approach to estimating losses (multiplying the estimated difference between actual and potential yield for 1976 by market price) and derived a total estimated loss of $52.5 milliion. While the difference appears relatively small, the traditional method only measures effects on producers. If the latter figure is compared with the producer loss

Table 4.1. Assessments of regional economic costs to agriculture from air pollutants.

Study	Year of Estimate	Region	Crops	Dose-Response Functions	Benefits of Control	Comments
Adams *et al.* (1982)	1976	Southern California	broccoli, cantaloupes, carrots, cauliflower, celery, lima beans, onions, potatoes, tomatoes, cotton, sugar beets	mixed set taken from existing literature	$43-$45 million	Damage functions generally based on visible leaf injury estimates by Larson and Heck (1976), with exception of cotton derived by Oshima (1973). Losses estimated as economic surplus ($35.1 million producer quasi-rents and $10.1 million consumer surplus) in 1976 dollars. Employs mathematical programming to compare "clean air" case with 1976 ambient levels.
Leung *et al.* (1982)	1975	California South Coast Air Basin	alfalfa, avocado, celery, lemon, lettuce, navel orange, valencia orange, strawberry, tomato	yield functions estimated from field data	$93-$103 million	Damage functions based on actual field information, ozone concentrations present at 61 monitoring stations and meteorological data (temperature, precipitation, relative humidity). Losses estimated as economic surplus ($45.8 million producer surplus and $57.3 million consumer surplus) in 1975 dollars. Employs econometric procedures to compare "clean air" case (no oxidant pollution) with ambient levels.
Page *et al.* (1982)	1976 to 2000	Ohio River Basin	soybeans, corn, wheat	field, outdoor/ indoor chambers	$278 million ($6.8 for 25 year period)	Damage functions based on crop loss estimates developed by Loucks and Armentano (1982). Losses estimated in terms of producer surplus for period 1976 to 2000 for tree electricity demand scenarios and expressed as net present values in 1975 dollars. Analysis compares "clean air" case versus one experiencing ambient ozone levels.
Smith and Brown (1982)	1980	Indiana	corn, soybean, wheat	from existing literature	$850-$49,216 per farm	A representative 720-acre farm in Indiana is analyzed with a linear programming model to generate estimates of crop losses from ozone. Estimated gain in farmers' income ranges from $850 to $49,215 (1980 dollars) depending on region and different yield improvement scenarios.

(continued)

Table 4.1 (continued)

Study	Year of Estimate	Region	Crops	Dose-Response Functions	Benefits of Control	Comments
Benson *et al*. (1982)	1979, 1980	Minnesota	corn, wheat, alfalfa, potatoes	synthesis of field, open and closed-top chamber data in literature	$30.5 million	Uses dynamic loss functions incorporating crop growth stage and ozone episodes. Farm level dollar losses obtained from econometric model of national commodity markets. Loss estimated in 1980 dollars and represents "worst" case O_3 situation, ignoring production effects outside Minnesota. If other regions included in analysis, worsening of ozone increases total gross returns to Minnesota producers by $67 million due to inelastic nature of commodity demand.
Dixon *et al*. (1983)	1978-1981	Illinois	corn, soybeans, wheat	producer's production and cost data	$55-$200 million	Uses "duality" approach to measure effects of ozone on producer's profits. Preliminary analysis suggests "reasonable" results in terms of physical ad economic loss estimates when compared with response results from NCLAN field experiments.
Adams and McCarl (1983)	1980	Corn Belt	corn, soybeans, wheat	from NCLAN literature and unpublished NCLAN sources	$668 million	Uses a sectoral model of U.S. agriculture to record effects of changes in Corn Belt yields due to alternative oxidant standards. Benefits of alternative federal standard (0.08 ppm) include effects on consumers' and producers'. Cost of relaxing the present standard to 0.16 ppm are approximately $2.0 billion.

from the economic analysis, the result is an approximately 50 percent greater loss estimate for the traditional procedure, largely because of the inability to accommodate offsetting price changes and producer mitigative adjustments.

Leung et al. (1982) estimated ozone damage to nine annual and perennial crops in the California South Coast Air Basin, representing some 40 percent by value of crop production in the region. Rather than use an experimentally based measure of dose-response, Leung et al. estimated yield loss with yield functions derived from secondary data. Specifically, crop yields for 1963 through 1975 were obtained from county agricultural commissioners' reports of yields realized by farmers. Principal component analysis (PCA, a technique in which highly correlated variables are replaced with one or two components that contain most of the information of the original variables) was used to transform monthly environmental data (such as ozone concentration, temperature, relative humidity, and precipitation) into yearly indices. Then yield was regressed on these indices using linear regression procedures. Finally, crop-yield reductions were estimated for 1975 by calculating the differences between actual yields with 1975 levels of ozone and yields predicted by the PCA linear response functions at zero ozone concentration. While PCA may be one means of reducing multicollinearity between the explanatory variables used to derive yield functions estimated from secondary data, there are several statistical problems associated with this analysis. These include: (1) extrapolation beyond the range of data for some functions; (2) the continued presence of collinearity among variables; and (3) the omission of some other important explanatory variables. The resulting response estimates also differed rather dramatically from experimentally derived response estimates.

Using the predicted yield adjustments from these yield functions to drive the analyses, Leung et al. (1982) then calculated changes in consumers' and producers' surplus to approximate the welfare effects of changes in agricultural supply brought about by air pollution. Demand and supply curves were estimated from data from 1958 to 1977 and then used to calculate 1976 losses of consumer and producer surplus from ozone exposure of $103 million.

Losses within the Ohio River Basin (Illinois, Indiana, Ohio, Kentucky, West Virginia, and Pennsylvania) were estimated by Page et al. (1982). The region is a major producer of corn, soybeans, and wheat; it also experiences oxidant levels sufficiently high to depress crop yields. Although the study examined two pollutants, SO_2 and O_3, the largest losses (approximately 98 percent) were attributed to O_3 levels. The yield reduction data were derived from Loucks and Armentano (1982), who synthesized experimentally determined crop loss data and extrapolated the results to air quality concentrations in the Ohio River Basin. This procedure and the resultant estimates involved extrapolations across fairly diverse crops and regions, casting doubt on the validity of the yield estimates.

Losses were measured at the producer level as changes in producers' income (quasi-rents) between clean air and ambient ozone levels and corresponding losses (minimal, maximum, and probable) were projected over the 1976 to 2000 period, and the estimated loss expressed in 1976 dollars.

The net present value of ozone-induced losses across the various loss scenarios for the 25-year period is approximately $6.8 billion, or an annual equivalent of $278 million. Not surprisingly, the bulk of these losses is estimated to accrue to the states with the largest agricultural production, Illinois and Indiana.

Some previous economic loss assessments (Manuel et al., 1981; Leung et al., 1982) utilize a crop by crop approach, so that substitution between crops is not considered. Smith and Brown (1982) assess the importance of substitution between differentially sensitive crops (acreage shifts between crops) in response to yield or to relative crop price changes with a farm level linear programming model. In theory, such substitution should occur if ozone (O_3) levels change, because soybeans are considerably more sensitive to O_3 than corn, and corn is more sensitive than wheat. Such relative sensitivity and its potential effects on economic estimates has been noted earlier by Adams and Crocker (1979), Adams et al. (1979), and Leung et al. (1978). Failure to consider such substitution may result in misestimation of changes of supply if producers have alternative crops or crop mixes to replace existing cropping patterns. Since the economic benefits from air pollution control legislation in most analyses are estimated in terms of changes in consumer and producer surplus caused by shifts in supply, it is important to determine if allowing crop substitution will significantly affect the estimation of benefits to be gained by reducing ozone levels.

As noted by Crocker (1982) and others, the failure to include crop substitution may bias benefit estimates from improved air quality in two directions. On the one hand, benefits to farmers from ozone reduction will be underestimated if farmers have minimized ozone damages by previously shifting acreage between crops in the response to yield changes. On the other hand, ignoring substitution effects on relative prices may result in an overestimation of net income gains to farmers. In addition, studies which fail to consider cross-crop substitution may lead to biased estimates of changes in consumer surplus from reduced ozone. Such studies will tend, ceteris paribus, to underestimate the increase on consumer surplus for crops which are more sensitive to ozone than other crops, and tend to overestimate the increase in consumer surplus for crops that are less sensitive.

The linear programming model utilized by Smith and Brown assessed the impact of four different yield improvement scenarios on acreage shifts among corn, soybeans, and wheat. Two of the yield improvement alternatives correspond to the maximum and minimum yield loss coefficients from ozone for the Ohio River Basin Region (ORBES report) estimated by Page et al. (1980). The remaining two alternatives relied on much smaller yield loss estimates: one-half and one-tenth of the ORBES minimum yield loss coefficients, respectively.

Comparison of each crop's acreage under different yield improvement scenarios reveals that as ozone levels fall, there is a shift from corn and wheat -- crops assumed to be more resistant to ozone damage -- to soybeans which are considered more sensitive to the presence of ozone. Damage estimates equal to or greater than the ORBES minimum yield loss estimate result in major shifts in cropping patterns as well as significant loss in net farm income. Allowing crop substitution increases the estimated economic gain to farmers of reducing ozone by 0% to nearly 20% depending on the region and the yield loss estimate.

A major limitation of this study for policy purposes is that only benefits accruing to producers are assessed. Crop demand was assumed totally elastic so that output price would not change when supplies shifted. Although such an assumption is valid at the firm level, the pervasive nature of ozone pollution suggests that the effects of price responses arising from aggregate supply shifts probably should be considered.

A comprehensive attempt to biologically model regional crop losses induced by ozone stress (Benson et al., 1982) also provides economic loss estimates for the state of Minnesota. The authors evaluated ozone-induced crop losses for alfalfa, wheat, and corn through the application of dynamic loss functions that specifically account for crop development and episodic exposure. These are synthesized from experimental data on fumigation and yield loss obtained by other researchers. The loss functions are then evaluated at the county level with actual or simulated 1980 ozone data.

The estimated potential yield losses occurring at ambient O_3 concentrations for each county are aggregated to provide a statewide crop loss. A national econometric model was then used to convert yield (production) adjustments for each crop into dollar losses, under alternative supply assumptions: (1) assuming ozone, and hence production, is unchanged in areas outside of Minnesota (analytically the same as the traditional procedure); and (2) assuming that ozone levels change nationwide and then accounting for supply and demand relationships for each crop as affected by production changes in all regions. The assumptions gave highly divergent estimates of losses to Minnesota producers. For example, the estimated dollar loss attributable to a worst case ozone level obtained from the first assumption is approximately $30.5 million in 1980 dollars. Conversely, when the econometric model accounted for price changes resulting from probable changes in production in all regions, it indicated that there would be a gain to producers of $67 million in the short run if ozone levels increased (in Minnesota as well as other production areas for these crops). These results, when combined with similar observations from Adams et al. (1982) and Leung et al. (1982) suggest the importance of assessment methodologies which account for regional market linkages and resultant price effects in performing economic assessments of a pervasive environmental problem.

Dixon et al. (1983) provide the first application of duality concepts to a major environmental issue such as air pollution in their analysis of the effects of ozone on Illinois cash grain farms. In addition to measuring the direct economic consequences of ozone on farmers' income, this analysis demonstrates the methodological utility of the duality approach, under some fairly restrictive conditions.

One of the primary objectives of this effort is to test whether a meaningful link can be established between the physical loss estimates generated under expensive and time-consuming controlled experimentation and the physical response information inherent in observed economic behavior (i.e., farmers' cost data). To explore this, Dixon et al. (1983) invoke duality concepts in developing profit functions for Illinois grain farms. These profit functions are estimated from a large sample of detailed cost and production data for Illinois farms and incorporate environmental variables (i.e., ozone, temperature, and rainfall) as well as the traditional economic variables.

By using duality procedures, the authors derived demand relationships for inputs as well as production effects for the environmental variables. The variable of interest is ozone. In most specifications, ozone is revealed to have a negative and significant (at the 5% level) impact on profit. When direct production effects (elasticity) of ozone are compared with NCLAN results obtained at Argonne National Laboratory in Illinois, the production responses appear to be reasonably close. Specifically, the aggregate (across three crops -- corn, soybeans, and wheat) output elasticity from Dixon et al. is -0.132 percent. For a 25% increase in ozone, it is estimated that output for the three crops would decline 3.3 percent. The same 25 percent increase using the Argonne data indicates an 11.7 percent and 3.7 percent decrease in output for Corsoy and Williams cultivars of soybean, respectively. For two corn cultivars, output would decline between 1.4 and 0.6 percent. The Dixon et al. estimate (of 3.3) lies between these estimates, a reasonable comparison for an aggregate measure.

Dixon et al. calculate that ozone resulted in an aggregate loss in profits to Illinois farmers of approximately $200 million in 1980. This estimate is based on the ozone elasticity with respect to profit (of -0.43 percent). Again, this result seems consistent with some previous loss estimates (Heck et al., 1983; Page, 1982). While the procedure applied by Dixon et al. provides encouraging preliminary results, certain caveats need to be noted. First, Dixon et al. had fairly rich economic and air quality data sets with which to work. It is unlikely that similarly detailed sets would exist at the national level, for example. Also, a number of statistical and estimation problems arose in this exercise. Even though some of these were resolved, the stability of the coefficients in several specifications is suspect and reinforces some well recognized difficulties in using secondary data to statistically sort out the effect of one environmental variable from among the many affecting yields.

A study of ozone effects on Corn Belt agriculture by Adams and McCarl (1983) uses a large-scale micro-macro economic model specification to measure effects of alternative oxidant standards on producers and consumers. The assessment is based on a detailed sectoral level programming model of U.S. agriculture accounting for major U.S. field crops as well as milk and livestock products. The analysis is driven by NCLAN response functions generated through the 1982 crop year and includes region-specific response data for corn, soybeans, and wheat. Changes in yields for alternative federal secondary oxidant standards as suggested by the NCLAN data provide the basis for a regulatory impact analysis.

The results of the analysis suggest that reduction in oxidants (lowering the present standard to 0.08 ppm from 0.12 ppm) would provide a net benefit of $668 million. Conversely, relaxing the standard to 0.16 ppm would result in a loss to consumers and producers of approximately $2.0 billion. In terms of distributional consequences, this analysis follows distributional shifts associated with changes in supply in the face of inelastic demand. That is, the 0.08 ppm scenario (of increased production) benefits consumers at the expense of producers, whereas the 0.16 ppm assumption results in the opposite situation.

Adams and McCarl also test the sensitivity of these regulatory results to different predicted yield changes. These differences in predicted yield arise from the wide range of NCLAN data available for use in assessments. These response functions predict somewhat different yields (for the same pollution or air quality standard assumption), depending on the crop cultivar, response model functional form, and water stress assumptions underlying the response function. By using different combinations of response function, Adams and McCarl compare the estimated benefits measures against the regulatory analysis (based on "most likely" data). The results indicate variations in benefits estimates of up to 60 percent around the most likely case. However, the authors argue that much of the variability can be eliminated through use of available prior information to select most appropriate response data for use in the regulatory analysis. Hence, additional biological data on cultivar sensitivity or response model form may have little payoff in improving the regulatory utility of the benefits estimates.

An implicit and limiting assumption of all of these regional estimates is that production levels in the excluded regions (the remainder of the United States) are not affected by the assumed changes in air quality imposed upon the regions under analysis. Given the possible crop price effects arising from production in other regions, such an assumption ignores the interregional market linkages and potentially biases the estimates of losses, as demonstrated in Benson *et al*. (1982).

4.5 National Loss Estimates

Properly structured national analyses overcome the fundamental limitations of regional analyses by providing for a fuller accounting of economic linkages. However, national assessments also tend to be more costly to perform and require more data. Predictably, there are fewer estimates of oxidant damages at the national than the regional level. Of these few national estimates, most use the traditional approach to quantify dollar losses. Hence, these analyses tend to ignore the economic concept of benefits discussed earlier. The principal improvements in recent national assessments over those appearing before 1978 (in the 1978 Oxidant Criteria document, for example) are dose-response information for a set of major commodities and somewhat better air quality data. Some national level estimates of air pollution damages are summarized in Table 4.2. As indicated in the table, the range of estimate is relatively small. Such relative consistency does not imply convergence on the "true" economic effects, however, as the analyses employ somewhat different crops, response information and assessment information and assessment approaches, as detailed below.

The recent national level estimates of ozone damages to vegetation include an assessment by the Stanford Research Institute (SRI) for the National Commission on Air Quality. The main intent of this updated version of the Benedict *et al*. (1971) study was to estimate the benefits of meeting the secondary national ambient air quality standards for ozone and sulfur

Table 4.2. Assessments of national economic cost to agricultural crops from air pollutants.

Study	Year of Estimate	Region	Crops	Dose-Response Function	Annual Loss Estimate	Comments
Stanford Research Institute (1981)	1980	U.S.	alfalfa, barley, beets, broccoli, cabbage, corn, cotton, hay, Irish potatoes, lima beans, oats, sorghum, soybeans, spinach, sweet corn, tobacco, tomatoes, wheat	field and chamber	$1.8 billion	Updated version of Benedict et al. (1973) study. Functions generally based on visible leaf injury. Loss measured in 1980 dollars for 531 non-attainment counties.
Manuel et al. (1981)	1980	U.S.	cotton, soybean	production (yield) functions estimated from secodary data on crop inputs and yields		Assessment of benefits attained by achieving alternative secondary national ambient air quality standards for SO_2 and suspended particulates. Estimated changes in producer and consumer surplus attained by a simple dynamic model. Model accounts for crop substitution in response to changes in output prices.
Moskowitz et al. (1982)	1978	U.S.	alfalfa	field	$22 million	DAMAGE model used actual oxidant measurements and the Oshima et al. (1976) dose-response function for alfalfa to estimate effects on yield. Loss measured in 1974 dollars for 485 counties.
Shriner et al. (1982) (Office of Technology Assessment)	1978	U.S.	corn, soybeans, wheat, peanuts	NCLAN field chamber data	$3.0 billion	Damage functions developed by EPA/NCLAN. Losses estimated in 1978 dollars at county level. Assumes a background or "clean air" oxidant level of 0.025 ppm (seasonal seven-hr average) ozone.
Adams and Crocker (1982b)	1980	U.S.	corn, soybeans, cotton	NCLAN field chamber data	$2.2 billion	Damage functions developed by EPA/NCLAN. Estimated farm-level demand and supply relationships with simple general equilibrium functions. Losses measured in 1980 dollars using economic surplus. Loss represents the difference between current production and production if a background ozone level of 0.040 ppm (seasonal seven-hr average) had been achieved.

dioxide accruing to 16 agricultural crops. Selection of crops was based on their economic significance and demonstrated sensitivity to air pollutants. The principal methodological differences between the earlier Benedict et al. approach and the more current effort include the use of a wider range of dose-response functions drawn from the recent literature (functions were developed to measure response to chronic as well as acute doses), updated production data from the 1974 Census of Agriculture and updated air quality and price information (similar to that of Moskowitz et al., 1980).

As in the Benedict et al. approach, the principal organizing units are counties. These 531 counties are those recorded as not being in compliance with the current oxidant national ambient air quality standard of 0.12 ppm. With alternative response functions and county-level data on air quality, the loss in potential yield and hence total production from oxidants and sulfur dioxide emissions was estimated. These physical loss estimates are then translated to a dollar loss by simply multiplying the reduction in production by the 1980 crop price for each commodity. The economic limitations of such an approach have been discussed in Section 4.2.1. The resultant damage estimate (or potential benefit of meeting the secondary national ambient air quality standards for ozone and sulfur dioxide) was reported to be $1.8 billion (1980 dollars) for agricultural crops. Of this total, the benefits of meeting the oxidant standard are far greater than the direct benefits of meeting SO_2 standards ($1747 million compared to $34 million). This is because the number of nonattainment counties for oxidants is nearly six times the number of nonattainment counties for SO_2. In addition, counties with high oxidant concentrations include most important agricultural areas, while those with high SO_2 concentrations are characteristically more urban. The damage from acute doses of oxidants only slightly exceeds that from chronic doses. A summary of the benefits to each of the nine Bureau of Census regions reveals that the East North Central Region (Ohio, Indiana, Illinois, Michigan and Wisconsin) would gain slightly less than one-half the total national benefits. Finally, it should be noted that the $1.8 damage estimate greatly exeeds the previous SRI damage estimate (Benedict et al., 1973) reported in Table 5.2, reflecting the sensitivity of such dollar-loss estimates to the data assumptions and time period employed.

In response to some of the biological limitations of the SRI model developed by Benedict et al. (1971), the DAMAGE model was constructed by Moskowitz et al. (1982) to estimate national-level damage from oxidants for alfalfa. Several data sources were utilized to produce more defensible estimates of biological damage. Actual EPA air quality measurements rather than emissions estimates were used to represent dose. The ozone dose-response damage function for alfalfa developed by Oshima et al. (1976) was used rather than the subjective sensitivity functions based on foliar injury developed by Benedict et al. (1973). In addition, crop yield statistics were obtained from the U.S. Census of Agriculture.

The DAMAGE model combined estimates of exposure, dose-response, and crop production data to yield estimates of direct loss. As with the SRI study, however, dollar loss was determined by simply multiplying crop value by percent loss. National level economic loss estimates from the DAMAGE model were found to be closely correlated to those attained by the SRI model, with the DAMAGE model estimating $23.9 million and the SRI model $21.7 million.

However, considerable variation in dollar loss estimates and percent loss among regions is evident within each of the dose calculations. Hence, the authors suggest that the dollar loss estimates are highly sensitive to the method of aggregating air quality measurements to represent dose. A related technical concern may be the application of the Oshima et al. (1976) dose-response function developed to estimate damage for one variety of alfalfa (Moapa 69) to estimating damage for other alfalfa varieties in the country.

Another study assessing the benefits to be gained by reducing air pollution was conducted by Manuel et al. (1981). Their investigation centered on estimating the potential benefits for cotton and soybean production of achieving alternative secondary national ambient air quality standards for sulfur dioxide (SO_2) and total suspended particulates (TSP). The estimated demand equation included the prices of soybeans, corn and substitutes. On the supply side, cross sectional data were utilized to estimate crop yields; variables included fertilizer per acre, lime per acre and SO_2 level. An acreage response for each crop is estimated as a function of the crop's expected price, the expected price of a substitute crop and government support programs for that crop. Supply was subsequently estimated as the product of the yield equation and the acreage response function. Estimated changes in producer and consumer surplus are attained by a simple dynamic model.

The Manuel et al. (1981) econometric model greatly improved on the traditional procedures used in the SRI and Moskowitz et al. (1982) analyses in that it includes the price effects across crops, and hence accounts for crop substitution in response to changes in output prices. The model framework also does not require the direct use of experimentally derived dose-response functions; instead, production function concepts are used to account for ozone and SO_2 impacts on production. However, as with any aggregate econometric approach, the model is unable to reflect compensatory input adjustments or the substitution which may occur as farmers choose to plant more of some crops and less of others because of relative yield changes.

A national assessment by Shriner et al. (1982) for the Office of Technology Assessment estimated the losses currently accruing to ambient ozone levels for four crops -- corn, soybeans, wheat, and peanuts. The study employed dose-response information from recent NCLAN experiments and simulated county-level ozone data generated by meteorologists at Research Triangle Park from available SAROAD monitoring sites. With the appropriate crop-response information and county-level ozone data in combination with 1978 Census of agricultural data on yields, percentage reductions were measured against a base ozone level of 0.025 ppm ambient concentration.

The estimated physical reduction in county production levels for each crop were then converted to a dollar loss estimate by the traditional procedure of multiplying by the county-level price. The aggregate loss (or difference between value of production at ambient levels and those at 0.025 ppm) for the United States was estimated at approximately $3 billion. The principal improvement of this study over the SRI assessment is in the use of NCLAN data.

Another estimate of nationwide damages attributed to oxidant pollution was developed by Adams and Crocker (1982b), who used information on plant effects of oxidants as a surrogate for the economic effects of acid deposition on agricultural systems. Their primary aim was to determine the sensitivity of estimates of economic loss to additional information on dose-response relationships. However, they also presented a numerical estimate of oxidant damage to three crops representing about 60% of the value of U.S. crop output (corn, for grain, soybeans, and cotton) using response data derived from 1980 and 1981 NCLAN oxidant experiments (Heck et al., 1982). The authors noted that their numerical example, while plausible, must be recognized as highly conditional given the nature of the underlying air quality data and problems of extrapolating from limited biological data.

In developing their estimates, Adams and Crocker used linear ozone dose-response functions derived from NCLAN results, and estimated farm-level demand and supply relationships directly with relatively simple general equilibrium functions. Demand was assumed to be represented by a price-dependent linear function, with farm-level price a function of quantity consumed and per capita income. Quantity supplied was assumed to be a function of prices of the same and competing commodities in the preceding time period. The response data, combined with the structure of the commodity markets in questions, were used to compare the benefits (Marshallian surplus) of progressively more stringent control schemes. The estimated difference between ambient ozone levels associated with the current standard of 0.12 ppm and a seasonal seven hour average of 0.04 ppm was approximately $2.2 billion. Assuming a log-normal distribution of ozone concentrations, a seven-hour seasonal mean ozone level of 0.04 ppm perhaps may be viewed as equivalent to a standard level of 0.08 ppm (not to be exceeded more than once a year).

These numerical estimates of benefits from decreasing ambient ozone levels are conditional on the assumption that ozone levels across a given region would not exceed that assumed level. That is, the analysis assumes that oxidant levels are uniform across all crop-production areas. If the actual concentrations are lower in most agricultural areas, then the Marshallian surplus accruing to the implementation of national standards would be overstated. Also, potential producer adjustments to changes in ozone levels from historical patterns are not addressed. As with most of the national assessments, improved data on oxidant concentrations within growing areas would help to reduce potential uncertainties in loss estimates from this type of assessment.

5.0: CONCLUSIONS

This paper has examined the benefits assessment literature on air pollution effects on agriculture and the underlying technical and economic basis for these assessments. The increased use of economic information in environmental regulatory analysis requires that both those who use as well as those who generate such information recognize the limits of these estimates. Although the ability to assess air pollution damage to vegetation and agricultural crops in particular has been enhanced by recent improvements in dose-response measurements and air quality data, many assessments are still plagued by both economic and technical shortcomings.

The review of assessment literature on agriculture indicates that treatment of some economic issues relevant to the measurement of benefits and cost from ozone and other pollutants in ambient air is still incomplete. Most regional benefits assessments now account for price effects and resultant producer and consumer adjustments, but there are other factors perhaps worth considering. Specifically, there is a need to account for producer adjustments such as input and output substitution effects through time and across regions, treatment of damages of perennial crops (fruits and nuts, forestry), and other long-term or dynamic adjustments to chronic pollution effects; the importance of accounting for the linkages between intermediate products and final products in assessments (e.g., the relationship between feed grains and livestock production); the linkages between international markets for the major export commodities; and the problem of evaluating economic damages to nonmarketed plants or plant groups, such as manifested through aesthetic effects on forest ecosystems.

The few recent estimates of national damage reviewed here do not display the same level of economic consistency as the regional efforts. Specifically, three of these recent studies employ the simple traditional approach used in earlier national assessments. Even the one study which addresses the importance of price adjustments does not treat the issue of economic linkages that would be required in an adequate national assessment. Thus, these estimates of potential benefits of control must be viewed with caution. Finally, as a percentage of total crop value, the national estimates are in the range of 4 to 6 percent and, as such, appear comparable with estimates of crop losses from other sources, such as disease (Boyer, 1982). Broader crop coverage, including perennials, more information on biological interactive processes, such as soil moisture and ozone, and fuller treatment of economic linkages, would be expected to refine the estimates of benefits of control and perhaps elevate the importance of agricultural control benefits in any regulatory accounting of benefits of ozone improvement.

5.1 The Importance of Economic and Biological Issues in Agricultural Benefit Assessments

Recent economic assessments of air pollution-induced vegetation losses demonstrate a general improvement in the use of economically consistent methodologies. Such assessments are now based on models which attempt to incorporate the physical, biological, and economic interactions which influence measurement of ultimate economic effects. Despite the use of improved economic methodologies, the results of these various studies detailed in Section 4.0 vary greatly because of lack of resolution concerning economic and biological issues. Such divergence may be attributable to: 1) different regions of the country are examined; 2) assessments are conducted for different time periods; 3) different agricultural crops are studied; and 4) different dose-response functions and air quality (dose) data are used.

There are several important features of these sources of variability that merit attention. First, most studies rely on county level crop statistics reported by the U.S. Department of Agriculture and the U.S. Bureau of Census. Air quality statistics are typically provided by the U.S. Environmental Protection Agency (e.g., the SAROAD air quality data). The crop statistics are considered to be reasonably accurate; the air quality statistics may not be as reliable. Rather than being based upon direct measurements, county level air quality estimates are frequently extrapolated from monitors located at varying distances from the specific county. In contrast, crop statistics are based upon actual or estimated county level data. Second, the majority of recent studies rely on dose-response functions derived from open-top chambers or cross-sectional analysis of field data. These analyses are usually based on measured or estimated reductions in yield at ambient or higher levels of pollution. Third, while plant physiology (i.e., stage of development and cultivar sensitivity) and climatic factors (i.e., precipitation) are known to influence the magnitude of plant response, most studies have not incorporated these factors into their bioeconomic models. Fourth, measures of loss range from estimates of monetary losses experienced by one group (e.g., producers) to more complex economic assessments of losses or benefits to consumers, producers, and intermediate users of the commodity, such as livestock producers.

The impact of these biologic, meteorological, and economic assumptions on the resultant benefits estimates is uncertain. However, refinements in data and procedures are expected to add to the credibility of future assessments. How these numbers are actually used in policy formulation and analysis is not well established, even in view of Executive Order 12291. Hence, the importance of resolving these sources of uncertainty becomes problematic until policymakers define the willingness to accept specific levels of Type II error in the regulatory process.

5.2 Limitations to Economic Analysis

In any assessment of benefits associated with reduced air pollution states, several significant qualifications are apparent. The first relates to the lack of physical or biological response information necessary to implement most bioeconomic assessment models. As reviewed earlier, these data include some type of crop response information by geographical area to estimate the change in marketable yield. Equally important are meteorological data on ambient and anticipated pollutant levels consistent with the geographical resolution of the assessment model.

The second qualification concerns the inclusion of all benefit values. The various methodologies suggested in Section 3 and used in assessments reported in Section 4 are capable of accounting for direct economic effects (primary and/or secondary benefits) on producers and consumer well-being. The exclusion of values typically not measured in market information, such as option, existence, and legacy values, results in an underestimate of the benefits. The magnitude of such an underestimate is difficult to assess. Some economists believe that the underestimates may be large in situations dealing with unique assets or major changes in an entire geographical region (e.g., Arrow and Fisher, 1974; Smith, 1974).

The third area of concern relates to the possibility that the physical or biological responses portrayed in the dose-response relationships may be irreversible. Once a certain level of damage has occurred, a reduction in an ambient air pollutant may not result in an improvement in environmental quality. For example, an irreversible long-range impact of air pollution could be the extinction of sensitive plant species. Use of current observed or inferred prices will not account for the genetic importance or diversity attributes of species and will underestimate the value of these plant resources to society. From the perspective of benefit valuation, this suggests that such potential loss of future opportunities to enjoy ecosystem amenities or outputs must at least be recognized in a conceptually correct benefit assessment.

An additional limitation to economic analysis pertains to the concern that the rate of damage may not be monotonically related to pollutant level, suggesting the presence of non-convexities (or "all or nothing" features). Crocker and Forster (1981) have suggested this possibility for certain types of environmental impacts where the dose-response relationship is such that, after a certain level of pollution, the rate of damages declines. Such a non-convexity would arise in the case of threshold effects for certain environmental parameters, implying that further pollution results in little or no impact. Besides rendering market or price information signals ineffective as guides toward economic efficiency, non-convexity also suggests that benefits of long-range air pollution control are greater and increase at a more rapid rate in a relatively unpolluted environment. The benefits of abatement would be lower once the rate of damages starts to decline. This implies that significant benefits may be associated with immediate air pollution control, while only smaller benefits will accrue if control and abatement take place after significant damage.

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