SECTION VI

VEGETATION AND AIR POLLUTION

PROBLEMS AND OBJECTIVES

Air pollution is a fact of contemporary Life. It is not only deleterious to human health, material, and household and commercial establishments as discussed in the preceding sections, but it is also recognized as a causal agent of damage to vegetation. Urban expansion and industrialization have resulted in deteriorated air quality in many major cities in the United States. Though social concern with the problem of contaminated air can be dated back to as early as the 13th century, the biological effects of degraded air are not thoroughly understood even now. Some progress has been made, however, in recent years. According to Naegele (1973), Laboratory and chamber studies of individual plants under somewhat controlled environments have contributed to the awareness of the complexity of plant response to toxicants. Acute and even chronic responses of plants to deteriorated air are being studied and documented.

There are three principal air pollutants of major interest to agricultural plants; namely, sulfur dioxide, fluorine compounds and smog. Regarding smog, there are two distinct types, with numerous intermediate grades: the London type, which is a mixture of coal smoke, fog and sulfur dioxide, and the Los Angeles type which is a mixture of ozone and peroxidized organic compounds. 1/

Studies on the effect of sulfur dioxide (SO_2) on vegetation are voluminous. Stoeckhard (1871) reported SO_2 injury to plants as early as 1871. Since then more than 700 articles have been published regarding the effects of SO_2 upon vegetation. The documents point to a great variation in plant responses to the pollutant. This variation in plant responses can be accounted for by such factors as genetic composition, stage of development, climatic factors, interactions between pollutants, the time of day of exposure, and soil moisture.

The effects of air pollution are customarily classified into two categories: (1) visible effects, which are identifiable pigmented foliar patterns as a result of major physiological disturbances to plant cells, and (2) subtle effects, which are not visibly identifiable, and may be identified when physiological change occurs in the plant. The disturbance of biochemical processes at the molecular Level is the cause of both the visible and subtle effects. Within the category of visible effects, acute and chronic injury can be identified. Acute injury is a severe injury as a result of a short-term, but high concentration of the pollutant. Chronic injury is light to severe injury; it develops from exposure to long-term low pollutant concentration.

1/ For a detailed discussion on the types of air pollutants causing damage to vegetation, see Thomas (1961).

The effects of oxidant on vegetation have been studied since the early part of this century. Oxidant or smog type symptoms were identified with the reaction product of ozone and reactive hydrocarbons. The symptoms were also associated with a new toxicant, peroxiyacety1 nitrate (PAN), which was generated experimentally by photochemical reaction of a mixture of nitrogen dioxide and reactive hydrocarbon (Stephen _et al_., 1960). Nitrogen dioxide is also a phototoxicant at high concentration levels. Benedict and Breen (1955) found tissue collapse with nitrogen dioxide concentration above 20 ppm.

Generally speaking, agricultural plants are adversely affected by air pollution vis-a-vis reductions in the quantity of output and/or degradation of the quality of the product. With the information on the determinants of the biological response of a plant to contaminated air, a reasonable, physical dose-response relationship could be constructed. In translating the physical damage function into a monetary damage function, the following factors should be considered: time and growing season, market value and price of the plant, the possibility of growing a different crop and the opportunity cost of the site for growing the plant.

Waddell (1974) identified two general approaches to assess the economic loss of plants due to air pollution.[1] One approach is to survey the damage loss on a statewide basis. Included in this category are the studies by Middleton and Paulus (1956), Weidensaul and Lacasse (1970), Feliciano (1972), Pell (1973), Naegele _et al_. (1972), and Millecan (1971).

Another approach is to construct predictive models by relating data on crop losses to crop values, pollution emission and meteorological parameters. The landmark study by Benedict and his associates (1971, 1973) at Stanford Research Institute (SRI) is probably the only study undertaken so far which provided some essential background material for further investigation. The SRI study estimated plant losses caused by air pollution in those U.S. counties where major pollutants (oxidants, SO_2, and fluorides) are expected to produce adverse effects on plants.

The major contribution of the SRI study is the provision of a wealth of data for the development of economic damage functions or of more sophisticated predictive models when better dose-response data are available. However, the study also contains the following weaknesses: (1) the damage factors were at best educated guesses and are subject to criticism; (2) yearly variations in climate and meteorology were not allowed for; (3) ornamentals were undervalued since only replacement costs were used as a proxy for aesthetic values; and (4) the subtle effects of air pollution which causes no visible injury were ignored. However, some subtle injuries were indeed included, contrary to most critics. The amount was a rough guess and, with the exception of citrus and grapes, could

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[1] See Waddell (1974) for a detailed discussion.

have been much larger or much smaller depending on the plant species. Latest information shows that such losses to forests and perhaps cotton in California are much greater than previously realized.[1]

A review of some previous damage estimates at both the national and state levels would give us a rough idea as to how serious the damage loss is because of air pollution. Benedict and his associates estimated the national total damage of visible injury to vegetation to be $132 million each year. Lacasse-Weidensaul estimated the amount of direct losses uncovered in the survey to be more than $3.5 million in Pennsylvania in 1969. Indirect losses were estimated to be $8 million. Feliciano reported the losses to agriculture in New Jersey due to air pollution were about $1.19 million in 1971. Naegele estimated direct economic losses for the 1971-72 season at $1.1 million. Finally, Millecan estimated a monetary loss of $26 million in crops in California in 1970.

In summary, the problems in the field of vegetation and air pollution are similar to those delineated previously in other categories, i.e., the lack of reliable scientific damage functions and the presence of a wide range of damage estimates. The primary objective of this section is to review the state of the art and derive, through existing documentation and data, an integrated economic damage function of air pollution on vegetation for purpose of prediction. The remaining part of this section contains the following subsections: Dose-Response Relationships, Economic Damage Functions, and Concluding Remarks.

DOSE-RESPONSE RELATIONSHIPS

Some crude dose-response relationships for various types of crops have been derived. O'Gara (1972) estimated the first such function for alfalfa under conditions of maximum sensitivity, as follows:

$$(C-0.33t) = 0.92 \qquad (VI-1)$$

where C is the concentration level to be estimated with respect to time t in hours. The constant 0.33 ppm represents a concentration that presumably can be endured indefinitely, i.e., the threshold level, without prolonged fumigation. That is to say that $C = 1.25$ ppm for $t = 1.0$.

The O'Gara equation was generalized by Thomas and Hill (1935) for any degree of leaf destruction and any degree of susceptibility. The generalized equation can be specified as:

$$t(c-a) = b \qquad (VI-2)$$

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[1] Personal correspondence with Dr. H. M. Benedict.

where t = time, hours, c = pollutant concentrations above a, a = threshold concentration below which no injury occurs, and b = constant.

With maximum susceptibility, the generalized equations were shown as follows:

$t(c-0.24) = 0.94$ traces of leaf destruction

$t(c-1.4) = 2.1$ 50 percent leaf destruction

$t(c-2.6) = 3.2$ 100 percent leaf destruction

Zahn (1963) developed an equation which modified the O'Gara equation and provides better fit over a longer period of time. The equation is shown as follows:

$$t = b\frac{1 + 0.5C}{C(C-a)} \qquad \text{(VI-3)}$$

The threshold level a was given as 0.1 for alfalfa; b is the dimensional resistance factor which incorporates the influence of environmental conditions.

An alternative experimental formula was suggested by Guderian, Van Haut (1960) and Stratmann (1963). The formula gives best fit to their observations for either short- or long-term exposures.

$$t = Ke^{-b(C - a)} \qquad \text{(VI-4)}$$

where K = vegetation life time, in hours, t; a, b, and C are the same as in (VI-3). These parameters may vary with species, environmental conditions, and degree of injury.1/

Although several physical dose-response relationships have been determined, economic damage functions for vegetations are largely nonexistent. The economic damage functions described in the following section employed input data on vegetation losses obtained from the Benedict study (1971,1973).

1/ The dose-response equations developed by Zahn, and Guderian, Van Haut and Stratmann were summarized in Environmental Protection Agency, Effect of Sulfur Oxides in the Atmosphere on Vegetation, op cit. The references were contained therein.

Benedict *et al*. derives crop loss estimates by using the product of three factors, i.e.,

$$\text{Crop Loss} = \text{crop value} \cdot \text{crop sensitivity to the pollutant} \cdot \text{regional pollution potential} \qquad \text{(VI-5)}$$

The regional pollution potential is a relative severity index of pollution, estimated for each county selected in the Benedict study on the basis of emission rates which are, in turn, derived from fuel consumption data. The relative sensitivity of various plant species to the pollutants was determined from a literature review. Each crop or ornamental was classified as to whether the part of the plant directly affected by the pollutants had high, medium or no economic value.

Despite the fact that the *ceteris paribus* type of dose-response functions has been developed and refined for certain types of vegetation, such functions are still unavailable for a majority of vegetations even now. Furthermore, the multivariate physical damage functions relating plant damage to several relevant explanatory factors are yet to be developed. In the absence of reliable plant dose-response functions, only rough estimates of economic damages for various plants can be derived.

ECONOMIC DAMAGE FUNCTIONS

Of more relevance to policymakers at both the national and local levels, however, are the monetary or economic damage functions which transform all aspects of dose-response relationships into one common unit of measurement, i.e., money. An attempt was made in this study to estimate such economic damage functions which relate economic losses of a variety of crops to air pollution concentration levels and climatological variables.

The crops and agricultural products for which the economic damage functions were estimated include corn grain, soybean, cotton, vegetable, other vegetable, nursery, floral, forestry, field crop, fruit and nuts, total crops, total ornamentals, and all plants. The selection of the crops is based mainly on the economic importances of these crops to the United States. However, it is understood that different cultivating procedures and methods as well as relocation of crop growing patterns in the United States will result in reduction in air pollution damage to crops.

A stepwise linear multivariate regression model was developed for determining the economic damage functions for the selected crops and plants, as follows:

$$\text{CROPL}_i = a + b\ \text{CROPV}_i + c\ \text{TEMB} + d\ \text{TEMA} + e\ \text{SUN} + f\ \text{RHM} + g\ \text{DTS} + h\ \text{SO}_2 + j\ \text{OXID} \qquad \text{(VI-6)}$$

where CROP denotes the economic loss (in \$1,000) of the ith type of crops by county from the Benedict study; $CROPV_i$ the output value (in \$1,000) of the ith type of crops by county; TEMB and TEMA stand for, respectively, the number of days in a year with temperature below 33°F and above 89°F; SUN represents possible annual sunshine days; RHM, relative humidity; DTS number of days with thunderstorm; SO_2 sulfur dioxide concentration or relative severity index; and OXID the oxidant relative severity index.

Data used for the regression analysis were obtained from prior studies on vegetation losses and the official publication on climatological data. As noted earlier, the disaggregated data on the vegetation losses and the values of the crops by county were obtained from the Benedict study. It should be pointed out that only the aggregate data on vegetation by regions are presented in Benedict et al. (1973). The crop data in the published form were integrated so as to preserve some anonymity about certain single sources of pollution. The data for CSO_2 and OXID were taken from Table 7 of Benedict et al. (1973), and the data for TEMB, TEMA, SUN, RHM, DTS were secured from the U.S. Department of Commerce, Local Climatological Data. Since the climatological data were not available for all counties or cities, data for a nearby city were, hence, substituted for the missing information for a number of counties. Finally, the annual mean level for SO_2 was taken from the U.S. Environmental Protection Agency, Air Quality Data - 1972 Annual Statistics.

Although estimates on crop values and crop losses are available for a total of 679 counties in the United States, a thorough examination of the data reveals that some counties have zero crop damage estimates and, hence, are not suitable for inclusion in the study sample. In addition, both climatological and pollution data are unavailable for a number of counties, but for which positive crop loss estimates were available. Only 74 counties have both positive crop loss estimates and data on climate and pollution levels. Thus they were selected for this study for deriving the vegetation economic damage functions.

The dependent and explanatory variables used in the regression analysis are described in Table VI-1. It should be noted that for sulfur dioxide two alternative measures were available: the first measure is the relative severity index constructed on the basis of pollutant emissions, concentration rate factor and episode days by Benedict et al. (1971), i.e., CSO_2..The second alternative measure, SO_2, is the annual mean level for sulfur dioxide ($\mu g/m^3$). Both measures were used in the regression analysis, and the regression results are separately reported in Tables VI-2 and VI-3. With regard to oxidants, the relative severity index for oxidants was also provided by Benedict et al. (1971). However, data on the annual mean level of oxidants are insufficient for this study. Thus, only the former measure was used in the regression analysis. The regression results containing oxidants are presented in Tables VI-2 and VI-4.

Some remarks on the regression results are in order. The values below the regression coefficients are standard errors with * indicating that they are significant at the 1 percent level. The signs of the regression coefficients

TABLE VI-1. VARIABLES USED IN ECONOMIC DAMAGE FUNCTIONS

A. Dependent variables - vegetation loss (in $1,000)

CORNL	Corn grain loss.
SOYBL	Soybean loss.
COTNL	Cotton loss.
OVGTL	Other vegetable loss.
NUSRL	Nursery loss.
FLORL	Floral loss.
FRSTL	Forestry loss.
FCROL	Field crops loss.
FRNTL	Fruit and nuts loss.
VEGTL	Vegetable loss.
TOCRL	Total crop loss.
TOORL	Total ornamentals loss.
ALPLL	All plant loss.

B. Explanatory Variables

CROPV	The value of the vegetation in question (in $1,000)
TEMB	Number of days with temperature 32°F or below.
TEMA	Number of days with temperature 90°F or above.
SUN	Possible annual sunshine days.
RHM	Relative humidity.
DTS	Number of days with thunderstorm.
SO_2	Annual mean level for sulfur dioxide ($\mu g/m^3$).
OXID	The relative plant-damaging oxidant pollution potential index.
CSO_2	The relative plant-damaging sulfur dioxide pollution potential index.

TABLE VI-2. ECONOMIC DAMAGE FUNCTIONS ON VEGETATION WITH POLLUTION RELATIVE SEVERITY INDICES (in $1,000)

	a	CROPV	TEMB	TEMA	SUM	RHM	DTS	CSO_2	OXID	R_2
(1) CORNL	4.4	0.001	0.02	0.09	-0.13	0.16	-0.041	6.73	-0.85	0.28
	(32.1)	(0.001)	(0.04)	(0.10)	(0.35)	(0.34)	(0.10)	(1.84)*	(2.18)	
(2) SOYBL	-2.2	0.003	0.01	0.04	-0.04		00.05	3.58	0.24	0.26
	(0.3)	(0.001)*	(0.03)	(0.07)	(0.28)		(0.74)	(1.49)*	(1.65)	
(3) COTNL	-5.8	0.0063	0.0006	-0.054	0.067	0.03	0.03	0.05	0.57	0.98
	(6.9)	(0.0002)*	(0.0094)	(0.028)	(0.077)	(0.07)	(0.02)	(0.40)	(0.48)	
(4) OVGTL	133.6	0.006	-0.03	-0.44	2.02	0.10	0.06		97.73	0.96
	(58.5)*	(0.001)*	(0.08)	(0.22)	(0.63)*	(0.65)	(0.21)		(3.71)*	
(5) NUSRL	-113.1	0.11	1.12	-0.19	0.35	-2.95	2.34		191.51	0.90
	(300.2)	(0.02)*	(0.42)*	(1.03)	(3.27)	(3.26)	(1.02)*		(33.09)*	
(6) FLORL	-616.4	0.10	0.93	-0.30	-0.79	-6.7	3.03		356.3	0.93
	(485.2)	(0.01)*	(0.57)	(1.41)	(4.37)	(4.4)	(1.37)*		(30.8)*	
(7) FRSTL	-616.4	0.071	1.93	-2.33	5.20	-1.88	4.77		370.52	0.96
	(485.2)	(0.003)*	(0.70)*	(1.63)	(5.34)	(5.22)	(1.71)*		(30.71)*	
(8) FCROL	520.5	0.003	0.28	1.17	-5.61	-3.26	-1.20		54.07	0.35
	(222.3)*	(0.002)	(0.32)	(0.82)	(2.44)*	(2.44)	(0.77)		(14.20)*	

TABLE VI-2 (Concluded)

(9)	FRNTL	-90.9	0.061	0.83	0.43	-2.28	0.28	1.74	121.3	0.82
		(281.2)	(0.006)*	(0.43)*	(1.00)	(3.18)	(3.09)	(0.98)	(18.02.)*	
(10)	VEGTL	-308.8	0.011	-0.33	-1.66	4.92	1.05	0.08	136.02	0.89
		(168.4)	(0.002)*	(0.23)	(0.64)*	(1.80)*	(1.85)	(0.60)	(10.69)*	

TABLE VI-3. ECONOMIC DAMAGE FUNCTIONS OF VEGETATION, WITH SULFUR DIOXIDE ANNUAL MEAN LEVEL (In $1,000)[a/]

	a	CROPV	TEMB	TEMA	SUN	RHM	DTS	SO_2 ($\mu g/m^3$)	R_2
(1) CORNL	10.6	0.0013	0.015	0.11	0.38	0.21		0.0008	0.10
	(31.0)	(0.0007)	(0.045)	(0.09)	(0.32)			(0.0960)	
(2) COTNL	-9.4	0.0063	-0.0004	-0.05	0.11	0.07	0.02	0.0005	0.98
	(6.2)	(0.0002)*	(0.0089)	(0.03)	(0.66)	(0.07)	(0.02)	(0.0195)	
(3) OVGTL	-803.0	0.009	-0.72	-1.05	9.44	6.82	-1.58	0.27	0.60
	(181.1)*	(0.003)*	(0.27)*	(0.77)	(1.95)*	(2.00)*	(0.67)*	(0.57)	
(4) NUSRL	-780.2	0.20	0.77	-0.98	7.79	1.19	1.87	0.40	0.85
	(350.6)*	(0.01)*	(0.51)	(1.25)	(3.81)*	(3.86)	(1.25)	(1.06)	
(5) FRSTL	-3,315.6	0.065	-3.52	-1.29	36.53	24.3	-3.05	2.30	0.87
	(785.0)*	(0.005)*	(2.90)	(1.17)	(8.57)*	(8.63)*	(2.82)	(2.44)	

[a/] For the 10 types of vegetations, the economic damage functions for CORNL COTNL OVGTL NUSRL and FRSTC yields a positive $S0_2$, while the remaining regression equations contain a negative S02. Only those five damage functions with a positive $S0_2$ are reported here.

TABLE VI-4. ECONOMIC DAMAGE FUNCTIONS ON TOTAL CROPS, TOTAL ORNAMENTALS AND ALL PLANTS (in $1,000)[a/]

	a	CROPV	TEMB	TEMA	SUN	RHM	DTS	OXID	$SO_2 (\mu g/m^3)$	R^2
(1) TOCRL	-375.7	0.011	-0.66	-6.81	12.93	-8.12	1.25	1,262.5		0.96
	(762.8)	(0.003)*	(1.07)	(2.80)*	(8.45)	(8.40)	(2.77)	(50.26)*		
(2) TOORL	-519.7	0.074	3.18	-1.61	-0.91	-6.36	9.09	769.31		0.92
	(965.5)	(0.004)	(1.38)	(3.28)	(10.59)	(10.63)	(3.42)	(60.87)		
(3) ALPLL	-2,251.3	0.039	0.50	-16.02	18.02	7.84	9.34	1,892.46		0.92
	(1,908.9)	(0.006)*	(2.73)	(6.76)*	(21.49)	(20.83)	(7.21)	(121.58)*		
(4) TOCRL	-8,247.2	0.032	-9.07	-16.40	93.30	74.72	-15.44		3.15	0.59
	(2,302.4)	(0.011)*	(3.38)	(9.03)	(26.04)*	(25.07)*	(8.76)		(7.19)	
(5) TOCRL	-5,927.4	0.069	-3.039	-4.03	61.38	46.27	-6.23		4.29	0.74
	(1,630.8)*	(0.008)*	(2.41)	(6.03)	(17.82)*	(17.97)*	(5.89)		(5.07)	
(6) ALPLL	-14,350.5	0.05	012.53	-24.98	150.45	128.37	-20.13		6.87	0.64
	(3,835.7)*	(0.01)*	(5.69)*	(14.52)	(43.62)*	(41.68)*	(15.06		(11.84)	

[a/] Equations (1) through (3) are economic damage functions of total crops, total ornamental and all plants with OXID as the sole pollution variable, while equations (4) to (6) are similar economic damage functions with S02 rather than OXID as the sole pollution variable.

are mostly compatible with _a priori_ expectations. Specifically, the sires of the pollution variables are-mostly correct except in equation (1) of Table VI-2 in which a negative sign for OXID appears. The negativity of OXID may be substantially attributable to the multicolinearity between the two pollution variables, CSO_2 and OXID (r =0.31) because OXID changes sign from positive to negative immediately when CSO_2 was picked up by the regression equation.[1]

Utilizing pollution severity indexes in the regression, a wide range of R2 is obtained, ranging from 0.25 for soybeans to 0.98 for cotton. However, when the annual mean level of S02 was included as the sole pollution variable, the independent variables explain a minimum of about 10 percent of the variations in corn losses and a maximum of 98 percent of the variations in cotton losses. The coefficients for the pollution severity indexes, i.e., CSO_2 which were constructed on the basis of pollutant emissions, concentration rate factor and episode days and OXID, are mostly significant at the 1 percent level whereas no coefficients for SO_2 are significant even at the 10 percent level. This result lends support to the hypothesis that it may not be appropriate to use pollution measures mostly recorded in the central city to represent countywide pollution level. Furthermore, it should be noted that the variable DTS was intentionally excluded from equation (1) of Table VI-3 to preserve the positive sign of SO_2.[2]

Using Equation (4), (5) and (6) in Table VI-4, economic damages of total crops, total ornamental and all plants were estimated for the 74 counties. The results are presented in Table VI-5. The table reveals that while total crop damages reached about $4 million in Los Angeles, Orange and San Diego counties all in California, San Bernadino suffered the largest ornamental damages and all plant damages in the order of $8.5 million and $10.6 million, respectively.

Intercorrelation among explanatory variables may not constitute a serious problem if prediction is the primary objective, provided, of course, the intercorrelation is expected to persist in the future. However, if multicolinearity results in an incorrect sign of the key variable, SO_2, a statistical interpretation of the SO_2 coefficient would be meaningless, and the exclusion of DTS is, hence, warranted.

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[1] It should be noted that RHM was intentionally excluded from equation 2 in Table VI-2 because the inclusion of RHM resulted in a negative OXID.

[2] When DTS is included, the regression equation, however, changes to read as follows:

$$\underset{(31.3)}{\text{CORNL} = 9.6} + \underset{(0.0007)}{0.0013}\ \text{CROPV} + \underset{(0.05)}{0.02}\ \text{TEMB} + \underset{(0.12)}{0.14}\ \text{TEMA} - \underset{(0.33)}{0.41}\ \text{SUN}$$

$$+ \underset{(0.35)}{0.27}\ \text{RHM} + \underset{(0.10)}{0.05}\ \text{DTS} - \underset{(0.097)}{0.004}\ SO_2$$

$$R^2 = 0.10$$

TABLE VI-5. ESTIMATED ECONOMIC DAMAGES OF TOTAL CROPS, TOTAL ORNAMENTALS AND ALL PLANTS[a]
(in $1,000)

(1) Counties	(2) Estimated Total Crop Damages[b]	(3) Estimated Total Ornamental Damages[c]	(4) Estimated All Plant Damages[d]
Jefferson, Alabama	--	--	--
Maricopa, Arizona	1,947	605	3,214
Alameda, California	3,708	1,527	5,677
Los Angeles, California	4,591	3,658	8,350
Orange, California	4,330	1,249	6,675
San Bernadino, California	3,780	8,481	10,606
San Diego, California	4,008	2,434	6,908
Fairfield, Connecticut	703	530	1,140
New Haven, Connecticut	847	423	1,290
New Castle, Delaware	136	2	89
Santa Rosa, Florida	--	--	--
Chatham, Georgia	--	28	--
Fulton Georgia	139	185	250
Honolulu, Hawaii	3,178	885	4,596
Cook, Illinois	149	766	888
Lake, Indiana	161	82	335
Marion, Indiana	356	144	602
St. Joseph, Indiana	442	106	692
Vanderburgh, Indiana	407	277	633
Polk, *Iowa*	522	58	841
Sedgwick, Kansas	159	103	301
Shawnee, Kansas	122	38	222
Wyandotte, Kansas	375	231	565
Boone, Kentucky	--	--	--
McCracken, Kentucky	281	217	407
Cumberland, Maine	381	209	549
Anne Arundel, Maryland	144	139	177
Baltimore, Maryland	281	1,257	1,192
Harford, Maryland	148	--	83
Howard, Maryland	84	--	--
Montgomery, Maryland	--	--	--
Prince Georges, Maryland	--	--	--
Berkshire, Massachusetts	--	--	--
Bristol, Massachusetts	280	87	311
Middlesex, Massachusetts	894	444	1,359
Worcester, Massachusetts	185	423	533
St. Louis, Missouri	196	230	405
Douglas, Nebraska	327	227	527
Lancaster, Nebraska	563	265	990
Rockingham, New Hampshire	117	333	286
Mercer, New Jersey	--	--	--
Bernalillo, New Mexico	--	--	--
Albany, New York	--	--	--
Erie, New York	294	389	835
Monroe, New York	--	--	--
Niagara, New York	257	--	405
Oneida, New York	--	--	--
Forsyth, North Carolina	114	51	142
Clark, Ohio	187	--	266
Cuyahoga, Ohio	151	322	458
Franklin, Ohio	--	--	--
Hamilton, Ohio	--	--	--
Jefferson, Ohio	--	--	--
Mahoning, Ohio	281	124	494
Montgomery, Ohio	72	42	180
Stark, Ohio	--	--	--
Summit, Ohio	--	--	--
Multnomah, Oregon	102	--	--
Indiana, Pennsylvania	--	--	--
Washington, Rhode Island	175	--	21
Greenville, South Carolina	--	--	--
Davidson, Tennessee	--	--	--
Hamilton, Tennessee	--	--	--
Knox, Tennessee	267	77	393
Shelby, Tennessee	303	387	595
Tom Green, Texas	--	--	--
Nansemond, Virginia	995	224	1,364
York, Virginia	803	327	1,079
King, Washington	834	1,249	1,876
Pierce, Washington	711	837	1,407
Spokane, Washington	--	286	--
Dane, Wisconsin	1,070	132	1,759
Milwaukee, Wisconsin	340	147	517
Natrona, Wyoming	--	--	--

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[a] "--" denotes that the estimates are either insignificant or unreliable.
[b] Estimates based on equation (4) in Table VI-4.
[c] Estimates based on equation (5) in Table VI-4.
[d] Estimates based on equation (6) in Table VI-4.

Utilizing the "average" economic damage functions presented in this section, the changes in crop losses brought about by changes in the pollution or climatological variables can be easily estimated. For the sake of illustration; but without loss of generality, consider equation (6) of Table VI-4. The partial elasticity of ALPLL with respect to SO_2 evaluated at their mean values (see Table VI-6) is

$$E_{PLSO_2} = 6.87 \times (20.5/790) = 0.18.$$

Thus, if the SO_2 level in the air is lowered on the average by 2 $\mu g/m^3$ from 20.5 $\mu g/m^3$ to 18.5 $\mu g/m^3$ (i.e., 10 percent reduction), then economic damage to all plants, on the average, could reduce by $74,220, $790,000 x 1.8 percent from $790,000 to $715,780. The partial elasticities for other variables of interest in the economic damage functions can be similarly computed, and the results are amenable to analogous interpretation.

CONCLUDING REMARKS

Economic damage functions estimated in this section are replete with conceptual difficulties. The task of translating physical damage functions into monetary damage functions involves a rather anthropocentric-egocentric evaluation procedure. This is generally the case because the evaluation, and subsequently adoption, of the physical damage functions by Benedict et al. is mainly based on our own value judgments rather than on any scientific substance. Furthermore, the damages suffered or anticipated by the receptors may well lead to changes in the market behavior, and hence, the market prices may not correctly reflect the welfare loss associated with the physical damages.[1]

In spite of the various conceptual difficulties associated with translating physical damages into dollar worth equivalents, economic damage functions, were estimated for a variety of vegetation in this study. In view of the numerous inherent weaknesses in the prior study and other conceptual and empirical difficulties associated with the estimation of economic damage functions, the damage functions presented in this section, though useful for estimating possible damage reductions brought about by pollution abatement programs, should be interpreted and employed with proper caution.

Finally, it is widely recognized that the best way to determine the occurrence and severity of an air pollution episode is to install a network of recorders to measure the daily and hourly concentration of various pollutants and the physical effects simultaneously. Although such nationwide networks have been

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1/ For a detailed discussion on some conceptual difficulties with economic damage functions, see Hans Opschoor, "Damage Functions, Some Theoretical and Practical Problems," in Environmental Damage Costs, Paris, OECD (1974).

TABLE VI-6. MEAN AND STANDARD DEVIATIONS OF VARIABLES IN VEGETATION DAMAGE FUNCTIONS[a]

Variable	Mean	Standard Deviation
CORNL	6.3000	13.5973
SOYBL	3.8838	11.0622
COTNL	2.8176	18.7760
OVGTL	32.3865	120.5110
NUSRL	72.2946	370.8508
FLORL	150.8000	622.7670
FRSTL	208.3392	894.3120
FCROL	48.7608	106.6920
FRNTL	56.2486	257.2594
VEGTL	58.2176	197.5723
TOCRL	436.6257	1502.4422
TOORL	353.8257	1334.1816
ALPLL	790.4486	2651.6519
CORNV	1199.6392	2347.7278
SOYBV	562.8405	1330.7283
COTNV	439.0622	3088.3767
OVGTV	992.6432	4300.7229
NUSRV	728.7108	1755.0623
FLORV	1441.2243	3055.6803
FRSTV	2734.4284	10586.1798
FCROV	6435.3541	8530.7033
FRNTV	1154.7284	3037.2926
VEGTV	1660.6703	5341.7627
TOCRV	11905.0000	16015.2235
TOORV	5576.9757	12421.3958
ALPLV	17473.4527	22764.5429
SO2	20.4595	17.7148
SUN	59.5135	6.6647
DTS	34.5811	18.8999
TEMA	26.2027	24.2735
TEMB	82.4595	40.6061
OXID	0.4586	1.0726
SCO2	0.7927	0.9200
RHM	58.8108	6.9394

[a] The values of crop losses and crop values are expressed in $1,000.

set up, the individual stations are unfortunately mostly located in the center of large metropolitan areas or industrialized areas. Few stations have been located in agricultural areas or in suburban areas where most of the vegetation is grown. Furthermore, a substantial amount of SO_2 is produced by power plants and various smelter operations which are generally located outside of SMSA's. This difficulty of a lack of meaningful information on pollution levels in suburban or rural areas has motivated earlier investigators to resort to fuel consumption, number of pollution episodes, and the tendency of atmospheric conditions to derive the air pollution damaging potential estimates. After all, it is imperative to conduct research directed at obtaining information on vegetation-at-risk isopleths for various counties in the United States, so that more reliable economic damage estimates for vegetation can be derived for policy decisions.

SECTION VII

AGGREGATE ECONOMIC DAMAGE COSTS AND FUNCTIONS: AN OVERALL VIEW

Air pollution constitutes a modern problem which goes beyond the technology of simply controlling the pollutants. The need for effective control is generally recognized, but arguments against control proposals also prevail. These arguments are mainly based on economic grounds--whether or not the cost of attaining a specified level of ambient air quality exceeds the economic benefit that would be realized from a control program. The regional damage estimates developed in the preceding six sections provide some of this much needed information, however crude it may be, for evaluating the economic feasibility of a specific air pollution control program.

This final section presents an overall view of the economic damages and damage functions of various receptors that were derived in the preceding six sections. Further, "aggregate" economic damage functions defined with respect to several effect categories are developed by regressing the aggregate damages to the same set of explanatory variables used earlier in the development of the "individual" effect economic damage functions. Aggregate damage estimates for selected categories of damaging effects are also computed and presented.

The economic damage estimates for the effect categories of human health, material, and household soiling are summarized in Table VII-1, for the 40 SMSA's having an SO_2 level equal or greater than 25 $\mu g/m^3$. These 40 SMSA's are listed in Column 1. Column 2 (HNC1) and Column 3 (HNC2) present, respectively, the low and the high damage estimates of human health; the material deterioration damage estimates of both paint and zinc as derived in Section V are summarized in Column 4 (MDC). Column 5 (TNSCO) contains the total net household soiling damages as described in Section IV. Based upon the low and high damage estimates of human health presented in Columns 2 and 3, respectively, two sets of low and high aggregate damage estimates for the three effect categories were estimated and presented in Column 6 (TNC1) and Column 7 (TNC2).

Specifically, the following two equations were used for computing HNC1 and HNC2 for the 40 SMSA's.

$$HNC1 = HNCSO_2 + HNCTSP \qquad (VII\text{-}1)$$

$$HNC2 = \text{Maximum of } (HNCSO_2,\ HNCTSP) \qquad (VII\text{-}2)$$

where HNCSO2 and HNCTSP are, respectively, the net health damages attributable to SO_2 and TSP. These two aggregate damage estimates were computed by summing the mortality and morbidity costs due to SO_2 and TSP derived in Sections II and III; namely,

TABLE VII-1. ECONOMIC DAMAGES DUE TO AIR POLLUTION, BY
RECEPTORS FOR SELECTED SMSA's
(in $ million, 1970)

(1) SMSA's	(2) HNC1	(3) HNC2	(4) MDC	(5) TNSCO	(6) TNC1	(7) TNC2
1. Akron, OH	10	18	7	16	33	41
2. Allentown, PA	8	15	3	16	27	34
3. Baltimore, MD	48	80	17	137	202	234
4. Boston, MA	49	52	26	117	192	195
5. Bridgeport, CT	3	5	6	3	12	14
6. Canton, OH	6	6	11	14	31	25
7. Charleston, WV	3	3	4	10	17	17
8. Chicago, IL	191	360	105	516	812	981
9. Cincinnati, OH	22	22	12	57	91	91
10. Cleveland, OH	55	93	49	216	320	358
11. Dayton, OH	18	18	9	39	66	66
12. Detroit, MI	129	161	55	294	478	510
13. Evansville, IN	2	2	2	5	9	9
14. Gary, IN	12	24	8	24	44	56
15. Hartford, CT	12	19	5	16	33	40
16. Jersey City, NJ	11	17	8	17	36	42
17. Johnstown, PA	4	4	1	10	15	15
18. Lawrence, MA	3	5	7	3	13	15
19. Los Angeles, CA	123	147	76	388	587	611
20. Minneapolis, MN	21	32	12	37	70	81
21. New Haven, CT	3	5	4	4	11	13
22. New York, NY	352	527	111	418	881	1,056
23. Newark, NJ	39	48	14	112	165	174
24. Norfolk, VA	13	13	3	29	45	45
25. Paterson, NJ	7	7	13	9	29	29
26. Peoria, IL	4	4	9	8	21	21
27. Philadelphia, PA	107	158	33	104	244	295
28. Pittsburgh, PA	45	79	30	147	222	256
29. Portland, OR	13	13	8	30	51	51
30. Providence, RI	16	25	9	20	45	54
31.. Reading, PA	5	5	4	15	24	24
32. Rochester, NY	13	15	7	27	47	49
33. St. Louis, MO	44	61	24	119	187	204
34. Scranton, PA	5	5	2	23	30	30
35. Springfield, MA	12	15	3	7	22	25
36. Trenton, NJ	3	3	2	5	10	10
37. Washington, DC	48	88	21	86	155	195
38. Worcester, MA	3	4	8	6	17	18
39. York, PA	4	4	2	9	15	15
40. Youngstown, OH	9	10	8	23	40	41
Total	1,475	2,166	736	3,134	5,349	6,040

functions. The regression results pertaining to overall human health damage are presented in Column 1 to Column 4 in Table VII-2. The overall economic damage functions for zinc and paint, for household soiling and for plants derived in the previous sections are also presented in the table in Columns 5, 6, 7, 8, 9, and 10.

The existence of an economic damage function does not in itself provide us with sufficient information to make any policy recommendations. Quantitative estimates of the magnitudes of the relationship are required. As discussed earlier, this information can be obtained directly from the estimated regression coefficients. The coefficients in the regression equation indicate the changes in the dependent variable in response to a one unit change in the associated explanatory variable ceteris paribus. The coefficients can be used for computing the elasticities under given conditions. A distinguishing feature of the concept of elasticity is that it is a unit free measure of the percentage change in the dependent variable with respect to the percentage change in the independent variable. Given the elasticity estimates, we are able to answer the question, "What would the effect of a reduction in the pollution level be, ceteris paribus, on the level of economic damages of various receptors?"

Table VII-3 contains estimates of a hypothetical reduction in the air pollution concentration level for the several pollution receptors analyzed and presented in Table VII-2. The first column in this table presents the dependent variables. Column 2 shows the estimated values of the coefficients of the SO_2 or TSP variables. The next two columns list the mean values of SO_2, TSP, and the economic damages of the various receptors. The estimated elasticity of economic damages of a particular receptor with respect to SO_2 or TSP, evaluated at the means of both variables, is found in Column 5. These elasticities indicate the percentage change in the economic damages that would result, on an average, from a 1 percent change in SO_2 or TSP.

Of particular interest to the policymaker is the effect of a given discrete change in the pollution level on the economic damages of a particular receptor. Assuming that the federal government is considering the implementation of a pollution control program which is expected to lower the pollution level, on the average, by 10 percent, the average benefit of a receptor can be calculated by multiplying the coefficient of SO_2 or TSP by 0.10 times the mean value of SO_2 and TSP. These estimates can be found in Column 6.

The study of Table VII-3 reveals that the partial elasticities of gross economic damages of the receptors included in our study vary from 0.004 to 1.28. Furthermore, a 10 percent reduction of the air pollution level would result in a decrease in the annual economic damages in the range of $0.01 million for plants (ALPLL) to $5.26 million for the soiling effect of zinc (SDCZ).

The implication of our study for pollution abatement strategies is obvious. Any effort to reduce the current pollution level appears to have a varyingly significant impact on the economic damages resulting from the harmful effects of air pollution. Admittedly, the implication of this study must be qualified

$HNCSO_2$ = Mortality cost due to SO_2 + morbidity cost due to SO_2

HNCTSP = Mortality ***cost*** due to TSP + morbidity cost due to TSP

Total material damages (MDC) in Column 4 is the sum of deterioration damages on both materials, zinc and paint. Specifically, it was calculated as follows:

$$MDC = DDCZ + DDCP \qquad \text{(VII-3)}$$

with DDCZ, and DDCP defined and computed previously in Section V.

Finally, Column 6 (TNC1) and Column 7 (TNC2), which represent the low and high human health damages, respectively, plus other damages, were calculated as follows:

$$TNC1 = HNC1 + MDC + TNSCO \qquad \text{(VII-4)}$$

$$TNC2 = HNC2 + MDC + TNSCO \qquad \text{(VII-S)}$$

An inspection of Table VII-1 reveals that while New York and Chicago SMSA's had the largest aggregate air pollution damages, in the order of $1 billion, the smallest air pollution damages occurred in Johnstown and York, Pennsylvania, in the magnitude of $15 million in 1970.

Total material deterioration damage, including deterioration for zinc and paint, amounted to $0.7 billion for the selected 48 SMSA's under study. The corresponding figures for net household soiling was estimated at $3 billion, respectively. The damage on vegetation for this nation was estimated, according to Benedict, to be $132 million. These damage figures employed in this study were taken from earlier studies which were completed under various stringent assumptions.

AGGREGATE ECONOMIC DAMAGE FUNCTIONS

In order to develop marginal equivalent economic damage functions for the purpose of predicting damage or benefit, and for designing pollution control strategies, the overall economic costs of human health in the presence of SO_2 ($HCSO_2$) and that in the presence of TSP (HCTSP) were respectively regressed not only against pollution and relative humidity, but also against other relevant socioeconomic and climatological variables, e.g., PWPO, PAGE, PCOL, PDS, DTS, SUN, etc. The least-squares regression technique was used with input from the 40 sample observations for estimating the economic damage

TABLE VII-2. ECONOMIC DAMAGE FUNCTIONS[a,b,c]

Dependent Variables	HCSO2	HCTSP	HCAP1	HCAP2	SDCZ	DDCZ	SDCP	DDCP	GRSOC	ALPLL
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Intercept	37,775	-9,939	-54,687	-46,751	-23,328.4	7,562.2	-141,199.7	-4.820.1	-25.621.0	-14,350.5
	(35,512)	(10,525)	(42,107)	(57,923)	(19,929)	(6,640.4)	(259.8)*	*887.2	*(52,347.0	(3,835.7)*
PWPO	0.02									
	(0.14)									
PAGE	189,112	74,828	100.580	146,324					3,432.3	
	(207,266)	(36.937)*	(179,860)	(204,915)					(2,199.5)	
COL	70	5	70	70					3,766.0	
	(89)	(16)	(83)	(89)					(1,460.0)*	
PD									2.3	
									(4.3)	
DTS	94	39	54	75					90.9	-20.13
	(196)	(35)	(156)	(195)					(219.3)	(15.06)
RHM	222	156	120	120	2,679.3	86.8	911.3	31.1	-1,219.8	128.37
	(489)	(94)		(518)	(1,750.2)	(56.7)	(235.3)*	(8.0)*	(610.7)*	(41.68)*
SUN		179	242	139	-235.0	-76.0	305.3	10.4		150.45
		(114)	(563)	(632)	(1,820.4)	(59.0)	(245.9)	(8.4)		(43.62)*
SO2	593		611	601	943.3	30.5	69.1	2.3		6.87
	(78)*		(74)*	(77)*	(171.6)*	(5.5)*	(23.2)*	(0.8)*		(11.84)
TSP		0.0003	0.00006	0.00004	148.1	47.9			226.4	
		(0.002)	(0.00009)	(0.00012)	(356.0)*	(11.5)*			(166.9)	
MANFV									78.9	
									(2.3)*	
ME					43.1	1.4				
					(3.4)*	(0.1)*				
YP					21.9	712.6	15.2	0.50		
					(18.9)	(615.5)	(2.6)*	(0.08)*		
HU							577.2	19.7		
							(3.4)*	(0.1)*		
CROPV										0.05
										(0.01)*
TEMA										-24.98
										(14.52)
TEMB										12.53
										(5.69)*
R^2	0.66	0.25	0.69	0.68	0.64	0.63	0.99	0.099	0.92	0.64

[a] The values in the brackets are standard errors of the coefficients, with * to indicate that the coefficient is significant at the 1 percent level. The coefficients and standard errors in equations (5), (6), (7), (8) (9) and (10) are reduced by a factor of 10^3

[b] HCSO2 = Overall health cost in the presence of SO_2, HCTSP = overall health cost in the presence of TSP.
HCAP1 = HCSO2 + HCTSP = high health damage estimates.
HCAP2 = Maximum (HCSO2, HCTSP) = low health damage estimates, SDCZ, DDCZ, SDCP, DDCP, GRSOC and ALPLL are defined previously in Chapters IV, V, and VI.

[c] The sample observations for HCSO2, HCTSP, HCAP1 and HCAP2 are the 40 SMSA's with SO_2 level equal or greater than 25 g/m³, whereas the sample observations for SDCZ, DDCZ, SDCP, DDCP and GRSOC are the 148 SMSA's with population greater than 250,000. In the case of ALPLL, 74 counties were selected in the sample observation.

TABLE VII-3. GROSS ECONOMIC DAMAGES CHANGES RESULTING PROM A 10 PERCENT REDUCTION IN THE POLLUTION LEVEL[a,b]

(1) Dependent Variables	(2) Coefficients SO_2, TSP (10^3)	(3) Mean Values of SO_2, TSP ($\mu g/m^3$)	(4) Mean Value of Economic Damages ($ million)	(5) Partial Elasticity E = (2)·(3)/(4)	(6) Economic Damage Reduction = 0.1·(2)·(3) ($ million)
HCSO2	593	47.25	5,575.7	0.050	2.80
HCTSP	0.0003	100.87	2,431.7	--	--
HCAP1(a)	611	47.25	8,007.4	0.004	2.89
(b)	0.00006	100.87	8,007.4	--	--
HCAP2(a)	601	47.25	6,789.2	0.004	2.83
(b)	0.00004	100.87	6,789.2	--	--
SDCZ (a)	943.3	55.73	107.3	0.480	5.26
(b)	148.1	93.81	107.3	0.130	1.39
DDCZ (a)	30.5	55.73	3.5	0.480	0.17
(b)	47.9	93.81	3.5	1.280	0.45
SDCP	69.1	55.73	150.0	0.026	0.39
DDCP	2.3	55.73	3.3	0.039	0.01
GRSOC	226.4	93.81	434.2	0.049	2.12
ALPLL	6.87	20.45	0.8	0.180	0.01

[a] This table is calculated on the basis of the 10 economic damage equations presented in Table VII-2.

[b] "--" denotes value smaller than $10,000.

by several theoretical and empirical factors. As discussed in the previous sections, the major difficulties often encountered in estimating air pollution damages include the lack of knowledge regarding the shapes of functions describing the relationship between air pollution and various receptors, and the lack of a satisfactory theoretical model specifying the way air pollution affects various receptors. The impossibility of accounting for all major factors which might affect various receptors, the lack of reliable formulations used for translating physical damages into monetary terms, and the presence of numerous econometric problems have also caused concern to investigators.

Despite the existence of these difficulties, this study represents a major step forward in our knowledge of pollution damages in that it seems to be the first attempt to construct essential frameworks of the physical and economic damage functions to calculate comparable regional damage estimates for the several important receptors--human health, material, and household soiling, however tentative they may be. More importantly, various aggregate economic damage functions instrumental for transforming the multifarious aspects of the pollution problem into a single, homogeneous monetary unit are tentatively derived and illustrated. It is hoped that these will be useful to policymakers as they make decisions on the implementation of programs to achieve "optimal" (where social MR = social MC) pollution levels for this country, although proper caution must be exercised in interpreting and employing the various economic damage functions presented in this study.

Finally, it should be noted that although the availability of information on average or marginal damages is instrumental in determining the optimal national or regional pollution control strategies, the current problem is far more complex than the question of balancing the benefits to polluters against damages inflicted on the receptors. The issues are pressing and not yet well specified. The basic difficulty in applying the recent research findings to accurately estimate the air pollution damage cost stems from our ignorance about the receptors at risk to air pollution. So far, few attempts have been made to identify who suffers, to what extent, from which sources, and in what regions.[1] At this moment, updating and expansion of the available crude estimates, which are generally restricted to certain regions, are urgently needed. To identify the population at risk to air pollution, and to measure the damage specifically for polluted regions are apparently the most logical steps in the area of future research.

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[1] We are aware of only one study in the area of estimating population at risk. Namely, Istvan Jakaces and G. Bradford Shea, Estimation of Human Population-at-Risk to Existing Levels of Air Quality, Enviro Control, Inc., Rockville, Maryland (February 1975). This study reports the number of people within each major social and economic classification who were exposed to 1973 levels of various air pollutants within each standard metropolitan statistical area and EPA regions. Estimates of the population at risk for other major receptors, e.g., material and vegetation, have not been derived to date.

SECTION VIII

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APPENDIX A

OPTIMAL POLICIES IN THE PRESENCE OF ENVIRONMENTAL POLLUTION: A THEORETICAL FRAMEWORK

Before we systematically present the economic damage and damage function of air pollution for a variety of receptors, a general equilibrium framework explicitly incorporating the effect of environmental pollution is described in this section. Optimal intervention policies are also derived in this framework for policy consideration. More importantly, optimal policy prescriptions are suggested for meeting the acceptable pollution levels predetermined by the authority.

For analytical purposes, the following assumptions are made:1/

1. Air pollution adversely affects social welfare.

2. There are two types of industries; pollution emitting and pollution nonemitting, and air pollution is a joint product of the commodities produced by the pollution emitting industry.

3. Air pollution adversely affects the productivity of the labor input used in other industries.

4. By holding capital constant, labor is the only variable factor of production in all industries in the short run.

The social utility function for the economy under consideration is written as

$$U = U(X_1, X_2, A) \qquad \text{(A-1)}$$

where X_1 and X_2 denote, respectively, the vectors of commodities produced by the first and the second industries. The first industry refers to one in which the labor productivity is adversely affected by air pollution, and the second industry consists of those firms which, in the process of producing commodities X_2, emit pollution into the air. A represents a vector of n pollutants existing in the air, i.e.,{$A = \{a_1, . . a_j, . ., a_n\}$.

The partial derivatives of U are subject to the following sign restrictions:

1/ The assumptions are made mainly for facilitating the exposition. Relaxation of any of the postulates will not affect the conclusions.

$$U_1 = \partial U/\partial X_1 > 0; \qquad U_{11} = \partial^2 U/\partial X_1^2 < 0$$

$$U_2 = \partial U/\partial X_2 > 0; \qquad U_{22} = \partial^2 U/\partial X_2^2 < 0$$

$$U_A = \partial U/\partial A < 0$$

In view of assumption (2), the amount of air pollution emitted to the air, A_e is proportional to X_2.

$$A_e = aX_2 \qquad \text{(A-2)}$$

where a is a matrix with elements showing the quantity of each type of pollutant being emitted per unit of the commodities produced by the industry 2.

Assumption (3) permits the production function of the first industry to be represented by

$$X_1 = F_1 \left[L_1 - bAL_1\right] \qquad \text{(A-3)}$$

where L_1 is the amount of labor employed in industry 1, and b is the vector with elements indicating the loss of efficiency in L_1 due to a unit of the jth pollutant produced by industry 2, j = 1,...,n. To ensure that net labor input is positive, it is imposed that $bA < 1$.

Since industry 2 is assumed to be unaffected by, or at least compensated for, air pollution, an externality or by-product, its production function is represented by

$$X_2 = F_2 (L_2) \qquad \text{(A-4)}$$

where L_2 is the amount of labor utilized in industry 2.

Also assume that there is a pollution control sector with the following production function

$$A_c = A_c (L_3) \qquad \text{(A-5)}$$

where A_c is the quantity of air pollution abated and L_3 the amount of labor utilized in the pollution control activities.

Thus, the pollution existing in the air at any point of time is simply the difference between the quantity of pollution emitted and quantity of pollution abated.

$$A = A_e - A_c = aX_2 - A_c(L_3) \qquad \text{(A-6)}$$

Finally, the economy is subject to a labor availability constraint

$$L_1 + L_2 + L_3 \leq L \qquad \text{(A-7)}$$

The first order optimality conditions for this economy which is subject to an environmental externality are.derived by maximizing (A-1) subject to the constraints (A-2), through (A-7) and

$$L_1, L_2, L_3, X_1, X_2, A \geq 0 \qquad \text{(A-8)}$$

Form the Lagrangean:

$$\emptyset = U(X_1, X_2, A) - \lambda\,[X_1 - F_1(L_1 - bAL_1)] - \beta\,[X_2 - F_2(L_2)]$$

$$- \gamma\,[aX_2 - aF_2(L_2)] - u\,[A - aX_2 + A_c(L_3)] - w\,(L_1 + L_2 + L_3 - \bar{L}) \qquad \text{(A-9)}$$

Partially differentiating (A-9) with respect to X_1, X_2, A, L_1, L_2 and L_3 yields:

$$\frac{\partial \emptyset}{\partial X_1} = U_1 - \lambda = 0 \qquad \text{(A-10)}$$

$$\frac{\partial \emptyset}{\partial X_2} = U_2 - \beta - \gamma a + ua = 0 \qquad \text{(A-11)}$$

$$\frac{\partial \emptyset}{\partial A} = U_A - \lambda \frac{\partial F_1}{\partial L_1^*} - bL_1 - u = 0 \qquad \text{(A-12)}$$

$$\frac{\partial \phi}{\partial L_1} = \lambda \frac{\partial F_1}{\partial L_1^*}(1-bA) - w = 0 \qquad \text{(A-13)}$$

$$\frac{\partial \phi}{\partial L_2} = (\beta+\gamma a) \frac{\partial F_2}{\partial L_2} - w = 0 \qquad \text{(A-14)}$$

$$\frac{\partial \phi}{\partial L_3} = -u \frac{\partial A_c}{\partial L_3} - w = 0 \qquad \text{(A-15)}$$

Note that the shadow prices of X , X and A are, respectively, λ, β and μ. Both λ and μ are positive by assuming nonsatiation in consumption of both X and X . μ is negative since $\partial U/\partial A < 0$. The interpretation of equations (A-10) through (A-15) is straightforward. The optimality in the presence of the pollution externality requires that $U_1/U_2 = \lambda/[\beta + a(\gamma-u)]$;

$$U_1/U_A = \lambda/(u + bL_1 + \lambda\frac{\partial F_1}{\partial L_1^*}) \quad \text{and } w = \lambda(1-bA)\frac{\partial F_1}{\partial L_1^*} = -u\frac{\partial A_c}{\partial L_3} = (\beta+\gamma a)\frac{\partial F_2}{\partial L_2}.$$

In view of (A-11), and remembering a > 0 the optimal policy is to impose a consumption tax of $a(\mu+\gamma)$ per unit of X_2. From (A-12), it is clear that a subsidy of $\mu + bL_1 + \lambda\frac{\partial F}{\partial L_1^*}$ should be given to consumers who suffer from the air pollution. In view of (A-13), a production subsidy of λbA per unit of X_1 is required for efficient production. Also in view of (A-14), a production tax of ya per unit of X_2 should be imposed. In short, the optimal policies in the presence of the environmental pollution involve a consumption and production tax on X_2, a consumption subsidy on A and a production subsidy on X_1.

ACCEPTABLE POLLUTION LEVEL

Suppose the pollution level is constrained by the authority not to exceed the statutory acceptable level. This problem amounts to introducing an additional constraint in the model.

$$A \leq A^* \quad \text{or} \quad aF_2(L_2) - A_c(L_3) \leq A^*$$

In this case, the first order conditions (A-14) and (A-15) should alter to

$$\frac{\partial \emptyset}{\partial L_2} = (\beta + \gamma a + \alpha a)\frac{\partial F_2}{\partial L_2} - w = o \qquad \text{(A-14')}$$

$$\frac{\alpha \emptyset}{\alpha L_3} = (-\mu - \alpha)\frac{\partial A_c}{\partial L_3} - w = o \qquad \text{(A-15')}$$

where α is the shadow price associated with the acceptable pollution constraint. The constraint will be binding because otherwise the objective can be attained without statutory regulation. This means $\alpha > 0$. It is clear, in view of (A-14') and (A-15') that the optimal interventions to constrain the pollution in the air not to exceed the acceptable level are to apply an additional tax of αa per unit of X_2 and a subsidy of α per unit of A_c to the pollution control sector of the economy. Thus, a penalty on the pollution producing industry coupled with a subsidy on the pollution abatement industry is the second best optimal combination of policies to achieve the objective of reducing the pollution concentration below the "threshold" level.

APPENDIX B

LIST A

SMSA'S WITH POPULATION OVER 500,000 (L)

	SMSA	Code	Population, 1970 (in 1,000)
1	Akron, Ohio	AKR	679
2	Albany-Schenectady-Troy, N.Y.	ALB	721
3	Allentown-Bethlehem-Easton, Pa.-N.J.	ALL	544
4	Anaheim-Santa Ana-Garden Grove, Calif.	ANA	1,420
5	Atlanta, Ga.	ATL	1,390
6	Baltimore, Md.	BAL	2,071
7	Birmingham, Ala.	BIR	739
8	Boston, Mass.	BOS	2,754
9	Buffalo, N.Y.	BUF	1,349
10	Chicago, Ill.	CHI	6,979
11	Cincinnati, Ohio-Ky.-Ind.	CIN	1,385
12	Cleveland, Ohio	CLE	2,064
13	Columbus, Ohio	COL	916
14	Dallas, Texas	DAL	1,556
15	Dayton, Ohio	DAY	850
16	Denver, Colo.	DEN	1,228
17	Detroit, Mich.	DET	4,200
18	Fort Lauderdale-Hollywood, Fla.	FOR	620
19	Fort Worth, Texas	FOR	762
20	Gary-Hammond-East Chicago, Ind.	GAR	633
21	Grand Rapids, Mich.	GRA	539
22	Greensboro-Winston-Salem-High Point, N.C.	GRE	604
23	Hartford, Conn.	HAR	664
24	Honolulu, Hawaii	HON	629
25	Houston, Texas	HOU	1,985
26	Indianapolis, Ind.	IND	1,110
27	Jacksonville, Fla.	JAC	529
28	Jersey City, N.J.	JER	609
29	Kansas City, Mo.-Kans.	KAN	1,254
30	Los Angeles-Long Beach, Calif.	LOS	7,032
31	Louisville, Ky.-Ind.	LOU	827
32	Memphis, Tenn.-Ark.	MEM	770
33	Miami, Fla.	MIA	1,268
34	Milwaukee, Wis.	MIL	1,404
35	Minneapolis-St. Paul, Minn.	MIN	1,814
36	Nashville-Davidson, Tenn.	NAS	541
37	New Orleans, La.	NEW	1,046
38	New York, N.Y.	NEW	11,529
39	Newark, N.J.	NEW	1,857
40	Norfolk-Portsmouth, Va.	NOR	681
41	Oklahoma City, Okla.	OKL	641
42	Omaha, Nebraska-Iowa	OMA	540
43	Paterson-Clifton-Passaic, N.J.	PAT	1,359
44	Philadelphia, Pa.-N.J.	PHI	4,818
45	Phoenix, Ariz.	PHO	968
46	Pittsburgh, Pa.	PIT	2,401
47	Portland, Oreg.-Wash.	POR	1,009
48	Providence-Pawtucket-Warwick, R.I.-Mass.	PRO	911
49	Richmond, Va.	RIC	518
50	Rochester, N.Y.	ROC	883
51	Sacramento, Calif.	SAC	801
52	St. Louis, Mo.-Ill.	STL	2,363
53	Salt Lake City, Utah	SAL	558
54	San Antonio, Texas	SAN	864
55	San Bernadino-Riverside-Ontario, Calif.	SAN	1,143
56	San Diego, Calif.	SAN	1,358
57	San Francisco-Oakland, Calif.	SAN	3,110
58	San Jose, Calif.	SAN	1,065
59	Seattle-Everett, Wash.	SEA	1,422
60	Springfield-Chicopee-Holyoke, Mass.-Conn.	SPR	530
61	Syracuse, N.Y.	SYR	636
62	Tampa-St. Petersburg, Fla.	TAM	1,013
63	Toledo, Ohio-Mich.	TOL	693
64	Washington, D.C.-Md.-Va.	WAS	2,861
65	Youngstown-Warren, Ohio	YOU	536

LIST B

SMSA'S WITH POPULATION 200,000-500,000 (M)

	SMSA	Code	Population, 1970 (in 1,000)
66	Albuquerque, N. Mex.	ALB	316
67	Ann Arbor, Mich.	ANN	234
68	Appleton-Oshkosh, Wis.	APP	277
69	Augusta, Ga.-S.C.	AUG	253
70	Austin, Texas	AUS	296
71	Bakersfield, Calif.	BAK	329
72	Baton Rouge, La.	BAT	285
73	Beaumont-Port Authur-Orange, Texas	BEA	316
74	Binghamton, N.Y.-Pa.	BIN	303
75	Bridgeport, Conn.	BRI	389
76	Canton, Ohio	CAN	372
77	Charleston, S.C.	CHA	304
78	Charleston, W. Va.	CHA	230
79	Charlotte, N.C.	CHA	409
80	Chattanooga, Tenn.-Ga.	CHA	305
81	Colorado Springs, Colo.	COL	236
82	Columbia, S.C.	COL	323
83	Columbus, Ga.-Ala.	COL	239
84	Corpus Christi, Texas	COR	285
85	Davenport-Rock Island-Moline, Iowa-Ill.	DAV	363
86	Des Moines, Iowa	DES	286
87	Duluth-Superior, Minn.-Wis.	DUL	265
88	El Paso, Tex.	ELP	359
89	Erie, Pa.	ERI	264
90	Eugene, Oreg.	EUG	213
91	Evansville, Ind.-Ky.	EVA	233
92	Fayetteville, N.C.	FAY	212
93	Flint, Mich.	FLI	497
94	Fort Wayne, Ind.	FOR	280
95	Fresno, Calif.	FRE	413
96	Greenville, S.C.	GRE	300
97	Hamilton-Middleton, Ohio	HAM	226
98	Harrisburg, Pa.	HAR	411
99	Huntington-Ashland, W. Va.-Ky.-Ohio	HUN	254
100	Huntsville, Ala.	HUN	228
101	Jackson, Miss.	JAC	259
102	Johnstown, Pa.	JOH	263
103	Kalamazoo, Mich.	KAL	202
104	Knoxville, Tenn.	KNO	400
105	Lancaster, Pa.	LAN	320

	SMSA	Code	Population, 1970 (in 1,000)
106	Lansing, Mich.	LAN	378
107	Las Vegas, Nev.	LAS	273
108	Lawrence-Haverhill, Mass.-N.H.	LAW	232
109	Little Rock-North Little Rock, Ark.	LIT	323
110	Lorain-Elyria, Ohio	LOR	257
111	Lowell, Mass.	LOW	213
112	Macon, Ga.	MAC	206
113	Madison, Wis.	MAD	290
114	Mobile, Ala.	MOB	377
115	Montgomery, Ala.	MON	201
116	New Haven, Conn.	NEW	356
117	New London-Groton-Norwich, Conn.	NEW	208
118	Newport News-Hampton, Va.	NEW	292
119	Orlando, Fla.	ORL	428
120	Oxnard-Ventura, Calif.	OXN	376
121	Pensacola, Fla.	PEN	243
122	Peoria, Ill.	PEO	342
123	Raleigh, N.C.	RAL	228
124	Reading, Pa.	REA	296
125	Rockford, Ill.	ROC	272
126	Saginaw, Mich.	SAG	220
127	Salinas-Monterey, Calif.	SAL	250
128	Santa Barbara, Calif.	SAN	264
129	Santa Rosa, Calif.	SAN	205
130	Scranton, Pa.	SCR	234
131	Shreveport, La.	SHR	295
132	South Bend, Ind.	SOU	280
133	Spokane, Wash.	SPO	287
134	Stamford, Conn.	STA	206
135	Stockton, Calif.	STO	290
136	Tacoma, Wash.	TAC	411
137	Trenton, N.J.	TRE	304
138	Tucson, Ariz.	TUC	352
139	Tulsa, Okla.	TUL	477
140	Utica-Rome, N.Y.	UTI	340
141	Vallejo-Napa, Calif.	VAL	249
142	Waterbury, Conn.	WAT	209
143	West Palm Beach, Fla.	WES	349
144	Wichita, Kans.	WIC	389
145	Wilkes-Barre-Hazleton, Pa.	WIL	342
146	Wilmington, Del.-N.J.-Md.	WIL	499
147	Worcester, Mass.	WOR	344
148	York, Pa.	YOR	330

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

This study is primarily concerned with evaluating regional economic damages to human health, material, and vegetation and of property soiling resulting from air pollution. This study represents a step forward in methodological development of air pollution damage estimation. It attempts to construct essential frameworks of the physical and economic damage functions which can be used for calculating comparable regional damage estimates for the several important receptors--human health, material, and household soiling--however,tentative the damage estimates may appear to be. More importantly, aggregate economic damage functions instrumental for transforming the multifarious aspects of the pollution problem into a single, homogeneous monetary unit are tentativel derived and illustrated. It is hoped that these results will be of some use to guide policymakers as they make decisions on the implementation of programs to achieve "optimal" pollution levels for this country. Given the experimental nature of the methodological and statistical procedures and the degree of uncertainty associated with the study results, a great deal of caution should be exercised in using the products of this research.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Physical Damage Functions Economic Damage Functions Air Pollutants - SO_2, Suspended Particulate Receptors - Health, Materials, Household Soiling, Vegetations Standard Metropolitan Statistical Areas Regions		

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