A Model for Estimating Air-pollutant Uptake by Forests : Calculation of Absorption of Sulfur Dioxide from Dispersed Sources

by C. E. MURPHY, JR., T. R. SINCLAIR, *and* K. R. KNOERR, *respectively with the Savannah River Laboratory, E. I. duPont de Nemours & Co., Aiken, S. C.; USDA Agricultural Research Service, Cornell University, Ithaca, N. Y.; and School of Forestry, Duke University, Durham, N. C.* *The information reported here was developed during the course of work done under Contract No. AT(07-2)-1 with the U. S. Energy Research and Development Administration.*

ABSTRACT.—The computer model presented in this paper is designed to estimate the uptake of air pollutants by forests. The model utilizes submodels to describe atmospheric diffusion immediately above and within the canopy, and into the sink areas within or on the trees. The program implementing the model is general and can be used with only minor changes for any gaseous pollutant. To illustrate the utility of the model, estimates are made of the sink strength of forests for sulfur dioxide. The results agree with experimentally derived estimates of sulfur dioxide uptake in crops and forest trees.

AS DEFINED BY SMITH *(1972)*, there are three levels of interaction between forests and air pollution. The most obvious and most studied interaction is at high pollution levels where there is visible air-pollution damage or mortality of forest trees. At a lower level of pollution concentration there may be no visible damage, but more subtle damage may occur, such as loss of productivity or changes in species composition. Finally at still lower concentrations there may be no damage or possibly even a beneficial effect on the forest. At this lowest concentration level, and perhaps at levels where the damage is small compared to the benefit from pollution abatement, forests can be effectively used as sinks for some types of air pollutants. The effective use of forested green belts around urban and industrial areas depends on absorption at these pollutant concentrations.

The amount of a particular pollutant that will be absorbed by the forest is related to the atmospheric processes and source geometry that affect the delivery of the pollutant to the forest and the type of interaction that takes place between the forest and the pollutant. The simplest source geometry is a dispersed source, which is approximated by many small closely-spaced sources. This arrangement leads to a pollutant concentration near the forest, which varies slowly in time and space. For this kind of geometry, pollutant uptake can be treated as one-dimensional, vertical diffusion with a quasi-steady-state boundary concentration. It is one of the simplest absorption geometries for a forest and is the case dealt with in this paper. More complex cases include absorption under plumes or multiple plumes that have rapidly changing pollutant concentrations in time and space and must be studied by using more complex three-dimensional analyses.

The types of interactions between the forest and a particular pollutant depend on the chemical and physical reactions between the pollutant and forest vegetation and soil. The common gaseous pollutants can be grouped roughly according to their physical and chemical reactions with the forest. Some pollutants are essentially unabsorbed by the vegetation, while other pollutants react with plant and soil surfaces or are metabolized inside the plant at a rate that may maintain a steady-state uptake for fairly long periods of time. Intermediate to these two types of pollutants are the pollutants that react transiently by adjusting to new equilibrium concentrations in the plants or soil when external pollutant levels change.

Sulfur dioxide is an example of a pollutant that is actively metabolized by plants and can have steady-state uptake rates for fairly long periods of time when the atmospheric concentration stays below 7 parts per hundred million by volume (pphmv) *(Martin and Barber 1971)*. Therefore its uptake rate by vegetative surfaces can be calculated by using a steady-state, one-dimensional model when the source of sulfur dioxide is of a dispersed nature.

THE MODEL STRUCTURE

A model designed to provide an estimate of pollutant uptake must describe the response of the vegetation-atmosphere system to the environment as it is related to three types of processes: (1) atmospheric diffusion, (2) diffusion near and inside the absorbing plant, and (3) the physical and chemical processes at the sink on or within the plant. The atmospheric-diffusion processes are the result of turbulent eddies, which are related to the state of the atmosphere and the physical structure of the underlying surface. One-dimensional, steady-state atmospheric diffusion with a sink term is described by the equation:

$$\frac{\partial}{\partial z}\left(K\frac{\partial C_a}{\partial z}\right) + S_c = 0 \qquad [1]$$

where

K = The turbulent diffusivity for mass transfer.

C_a = The pollutant concentration (mass/volume) in the air.

z = Height above the ground.

S_c = Sink strength at height z.

The sink strength term is often zero for many pollutants in the atmosphere above the stand. Within the vegetative canopy it is the divergence of the absorption by the vegetation with height.

In the vegetative canopy, the turbulent diffusivity is a function of eddy size and the fluctuation velocity with which the eddies move. The eddy size or equivalent mixing length must be no larger than the open space available for rotation in the stand. The largest openings are the spaces between the individual trees. Smaller eddies are generated in the wake of canopy elements such as leaves or branches. The fluctuation velocity, which can be visualized as the speed with which the eddies rotate, is usually assumed to be proportional to the shearing stress at any level in the canopy. The defining equations are *(Cionco 1965, Takeda 1963)*:

$$\tau = \rho K_m \frac{du}{dz} \qquad [2]$$

$$\frac{d\tau}{dz} = \rho C_d \frac{dA}{dz} u^2 \qquad [3]$$

$$K_m = \iota\sqrt{\Gamma\rho} \qquad [4]$$

where

τ = Shearing stress.

ρ = Density of air.

K_m = The turbulent diffusivity for momentum transfer.

u = Wind speed.

C_d = Drag coefficient of the canopy surfaces.

A = The surface area of the canopy.

ι = The mixing length for momentum transfer.

Equations 2, 3, and 4 can be arranged for a simultaneous integration with height providing values of shearing stress, wind speed, and momentum with height, given a means of determining the mixing length. The procedure presented here used the equation

$$\iota = \iota_c X_s + k\,\overline{S}_P\,(1 - X_s) \qquad [5]$$

where

l_c = Mixing length inside the crown.

X_s = Relative cross-sectional crown area at a particular height.

k = Von Karman's constant ($\simeq$0.35).

$\tilde{S}_P$ = The average distance between tree crowns.

The spaces between elements within the crown are small compared to the spaces between crowns at most heights in the stand, and thus the values of mixing length inside the canopy are also small, tending to make the effect of the first term on the right-hand side of equation 5 small compared to the second term.

In the turbulent boundary layer above the canopy and in sections of the canopy where there is little surface area to produce drag, equations 2 through 4 can be greatly simplified. In these regions the shearing stress is approximately constant, and the divergence of shear is nearly zero. The value of the mixing length changes approximately linearly with height from the reference height where the shearing stress becomes constant. The constant of proportionality used in the calculations presented later was von Karman's constant ($\simeq$0.35). In the region of the boundary layer above the stand, this value must be corrected to take into account the effect of buoyancy caused by the exchange of sensible heat at the forest canopy. The correction is calculated by using the equations derived by Businger et al. *(1971)* and Paulson *(1970)* and a value of sensible heat flux determined by a surface energy balance, using the Penman-Monteith formula *(Monteith 1965)*.

The sink strength term in equation 1 is determined by the diffusion into the sink area and the absorption process. The diffusional process near vegetative elements is proportional to the concentration gradient and inversely proportional to the series of diffusional resistances in the flow path. In contrast to atmospheric diffusion, which is dominated by turbulent processes, the diffusion near the sink is largely molecular in nature. For materials like sulfur dioxide, which are absorbed inside the canopy leaves, these relationships are expressed by the equation:

$$S_c = \frac{dA}{dz}\left[\frac{SC_a - C_i}{S\,(r_a + r_s) + r_i}\right] \qquad [6]$$

where

S = The solubility of sulfur dioxide in the cell water.

C_i = The concentration of sulfur dioxide at the sink.

r_a = The leaf boundary layer resistance.

r_s = The leaf resistance associated with diffusion through the stomata in the leaf epidermis.

r_i = The diffusion resistance associated with the cell walls and the cytoplasm.

The boundary layer resistance is proportional to the square root of the leaf aerodynamic length divided by the wind speed. The stomatal resistance is often a complex function of light intensity, temperature, and water stress. When the water uptake from the roots is not limited by soil-water stress, a reasonable approximation of stomatal response can be calculated from *(Gaastra 1959)*:

$$r_s = a + \frac{b}{I + I'} \qquad [7]$$

where

a,b,I′ = Empirical constants.

I = Light intensity incident on a leaf.

The light intensity incident on a tree leaf will be a function of the angle of incidence of the light, the light intensity above the canopy, the leaf angle, and mutual shading of leaves in the canopy. These are incorporated in the model by using an exponential decay of direct beam and diffuse light with cumulative leaf area into the canopy. This results in estimates of the area in direct beam light and of the intensity of direct beam and diffuse light at any given height in the canopy. Separate resistances based on sunlight and shade intensities are calculated, and a weighted mean resistance based on the relative area in direct sunlight and shade at a given height in the canopy is used in equation 6.

The internal resistance in equation 6 is associated with diffusion through the liquid cell cytoplasm. The value of this resistance and its variation are difficult to determine. We have made an estimate on the basis of internal diffusion resistances calculated from photosynthesis data. The data used were from a series of experiments on phytotron-grown loblolly pine seedlings *(Gresham 1972)*. The calculation of resistance averaged very close to 20 sec/cm *(Sinclair 1972)*. This value is higher than is often found in other experiments. However, since the objective of this simulation is to evaluate the potential of forests as sinks for sulfur dioxide, we decided to use this value, which gives a conservative estimate of absorption.

The solubility of sulfur dioxide in water is very high; therefore the amount going into solution in the cytoplasm of the leaf cells should be large. The mechanism for sulfur dioxide solubility has two components: a reversible chemical reaction converting the gas to soluble sulfurous acid, and normal gas solubility in a liquid. The total equilibrium solubility is given by the equation

$$S = \frac{1}{S_g} + \frac{-H_c + \sqrt{H_c^2 + 4\,K_s\,C_i/S_g}}{2\,C_i} \qquad [8]$$

where

S_g = The gas solubility (Henry's law) constant.

H_c = The hydrogen ion concentration.

K_s = The equilibrium constant for the sulfur dioxide - sulfurous acid reaction.

C_i = The concentration of sulfur dioxide in the air at the air-liquid interface.

At a temperature of 25°C, the Henry's law constant has a value of 0.0332, and the equilibrium constant is 0.0130 moles/liter *(Johnstone and Leppla 1934)*. The values of both these parameters, which are very temperature-dependent, are given over the temperature range of 0°C to 50°C in Hales and Sutter *(1973)*, who also provide a correction factor that must be used at very low values of atmospheric sulfur dioxide concentration.

The internal sulfur dioxide concentration at the sink site in the absorbing cells is related to the nature of the absorption process. Since sulfur is a metabolite of plants, it is reasonable to believe that at least some part of the absorption process is from the synthesis of organic sulfur compounds. Faller *(1972)* has shown that all of a plant's sulfur requirements can be supplied by foliar absorption of sulfur dioxide. In fact, this will be the preferred source for the aerial organs, given the choice of translocating sulfate compounds from the soil or using sulfur dioxide absorbed from the atmosphere. The level at which this type of reaction becomes saturated can be estimated from experimental data. Martin and Barber *(1971)* have shown that the absorption rate versus atmospheric sulfur dioxide concentration of a narrow hedge is linear up to a concentration of 6.0 parts per hundred million by volume (pphmv) where there is a sharp break above which the absorption rate is constant. Bennett and Hill *(1974)* present data showing that there seems to be no additional metabolic cost, as measured by depressed photosynthetic rate, in barley at atmospheric concentrations of 5 pphmv, but there was a reduction of 2 percent at 10 pphmv. Roberts *(1974)* indicates that a *Pyracantha* seedling can continue steady-state absorption of sulfur dioxide for more than 6 hours at an atmospheric concentration of 100 pphmv.

The conclusion that can be drawn from these studies is that the absorption mechanism is not saturated below values of 5 pphmv and may be able to remain unsaturated for some species above this level. Since National Ambient Air Quality Standards for the United States are 3 pphmv on a yearly mean and 14 pphmv for the 24-hour average, the absorption by forests will often take place under conditions where the metabolic uptake is not saturated. Under these circumstances it seems reasonable to assume that the concentration at the uptake site approaches zero.

Equations 1 through 8 are the basic relationships needed to model the uptake of sulfur dioxide by forest vegetation. The only additional information is the boundary conditions appropriate to a particular environment.

MODEL IMPLEMENTATION

The equations of the model were coded in the Continuous System Modeling Program (CSMP) developed by IBM *(1972)*. This language was chosen over more general-purpose, higher-level languages like FORTRAN or ALGOL because of the large library of subprograms used for systems simulation that are part of the compiler. The leaf area, crown cross-section, and solubility functions were entered as tables, and a standard linear-interpolation program was used to find the values at the appropriate heights and temperatures in the stand. Integration of equations 1, 2, and 3 was accomplished by using a fixed-step Runge-Kutta routine. Integration was started at the bottom ($z=0$) of the stand with values of sulfur dioxide flux, sulfur dioxide concentration, wind speed, and shearing stress. Integration to the highest point desired provided values of these same variables at the upper boundary. It was arbitrarily decided to set upper boundary conditions of sulfur dioxide concentration and wind speed. The sulfur dioxide concentration and the shearing stress at the bottom of the stand were varied until values were found that produced the desired values of sulfur dioxide concentration and wind speed above the stand.

In addition to the boundary values needed for the integration and the tables of leaf area and tree cross-sectional area, other user-supplied inputs are needed to run the program. The leaf aerodynamic length, the constants of the stomatal function, and the other stand data were estimated from a detailed study carried out in a loblolly pine stand as part of the U.S. International Biological program (*Higgenbotham 1974, Gresham 1972, Murphy et al. 1973*).

An energy balance is calculated for the stand to provide values of sensible heat flux for the calculation of diffusivities for mass transfer in equation 4. Input for the energy balance is the incident solar radiation, the incident terrestrial sky radiation, the air temperature, and air humidity above the stand. Two standard cases have been calculated, using idealized values of the climatic input which closely match the average conditions for the coldest and hottest months of the year at the Savannah River Plant, Aiken, South Carolina. The radiation balance is calculated by using the earth-sun radiation geometry for the 15 January and the 15 July to provide estimates of incoming short-wave radiation. Brunt's equation was used to provide estimates of incoming terrestrial sky radiation (*Sellers 1965, chapters 3 and 4*). The net radiation calculated by this method is partitioned between sensible and latent heat transfer by using the Penman-Monteith equation (*Monteith 1965*). Daily air temperature and dew-point temperature (humidity) vary sinusoidally with lags of 3 hours and 6 hours behind the solar-radiation maximum. Values of the required stand structure and climatic data for the two stand conditions are given in table 1.

Table 1.—Input data

Parameters		January 15	July 15
Stand parameters:			
Leaf area index		6.0	9.9
Aerodynamic leaf length (cm)		0.1	0.1
Constants of stomatal resistance equation	a (sec/cm)	3.4	3.4
	b (sec-ly/cm-min)	0.19	0.19
	I' ly/min	0.003	0.003
Drag coefficient of leaves		0.02	0.02
Climatic parameters:			
Average air temperature (°C)		7.9	27.4
Amplitude air temperature (°C)		6	6
Average dew-point temperature (°C)		2.5	21.8
Amplitude dew point temperature (°C)		2	0.5
Wind speed (cm/sec)		260	175
Day length (hr)		8	12

RESULTS AND DISCUSSION

The results of simulations for 2 days representing climatologically average clear days during January and July at the Savannah River Plant site near Aiken, South Carolina, are illustrated in figures 1 and 2. The diurnal patterns are similar. The uptake of sulfur dioxide is at a minimum in the morning and evening and at a maximum sometime before noon. This is inversely related to the average stomatal resistance of the canopy, demonstrating the large effect of this resistance expressed in equation 6. The diurnal pattern of stomatal resistance is a result of our assumption that the resistance is a function of light intensity.

The effect of temperature on the solubility of sulfur dioxide is demonstrated by the uptake maximum occurring before the minimum stomatal resistance at noon. This is because we have assumed that the maximum temperature lags the maximum solar radiation by 3 hours. The solubility of sulfur dioxide in water is inversely related to temperature; thus the maximum absorption takes place at the coincidence of a low stomatal resistance and a high solubility of sulfur dioxide during the cooler morning period.

These results are further illustrated by figures 3 and 4. Figure 3 shows the instantaneous profiles of wind speed, crown cross-section, and sulfur dioxide concentration at 11:00 am of the diurnal simulation shown in figure 2. Figure 4 shows the same conditions except that the radiation inputs to the model are characteristic of a uniformly cloudy sky. The incident solar radiation was lowered from 1.12 ly/min to 0.42 ly/min. The lower incident radiation results in a higher average stomatal resistance at every height in the canopy, lowering the sulfur dioxide uptake by 27 percent. The lower uptake results in higher sulfur dioxide concentrations in the canopy.

A comparison of the total uptake for the January day, 0.29 kg/ha, and the July day, 0.58 kg/ha, shows the type of annual variation that can be expected. As illustrated in figures 1 and 2, one of the sources of this variation is the shorter day length during January. However, even the instantaneous uptake values are lower in January. This is caused by a lower leaf area in January than in July. Although a lower average stomatal resistance might be expected during the winter because of the lower incident solar radiation, this is not the case because there is more shaded leaf area in the denser summer canopy. The effect of the average stomatal resistance is reflected in the fact that uptake per unit leaf area is greater in the January simulation than the July simulation as shown in table 2.

Thus the diurnal pattern of sulfur

Figure 1.—A simulation of the diurnal pattern of sulfur dioxide uptake, net radiation, temperature, and average stomatal resistance for a clear day characteristic of Aiken, South Carolina, during January.

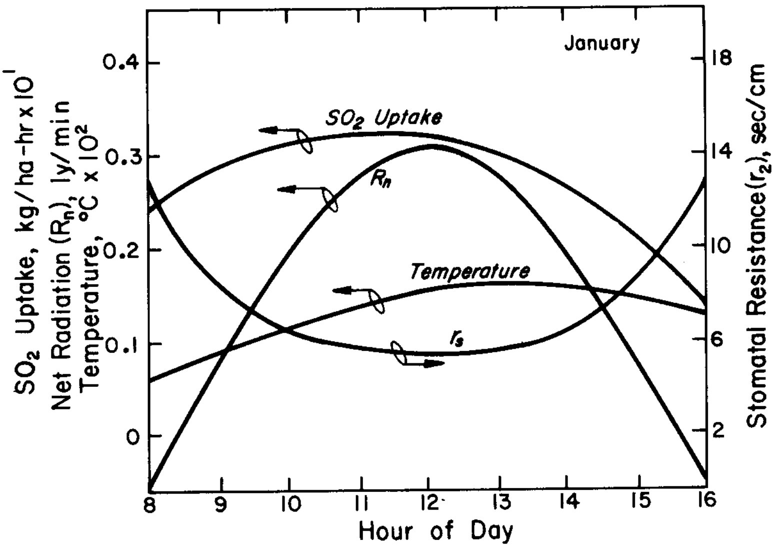
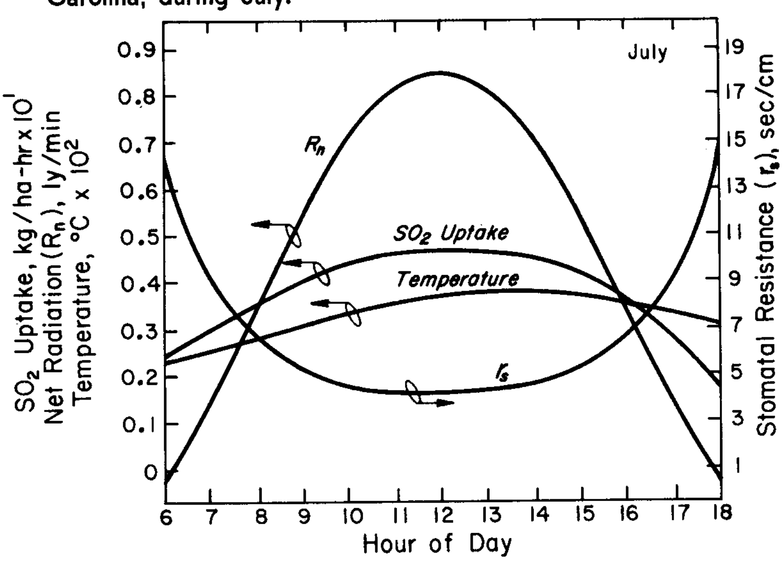


Figure 2.—A simulation of the diurnal pattern of sulfur dioxide uptake, net radiation, temperature, and average stomatal resistance for a clear day characteristic of Aiken, South Carolina, during July.



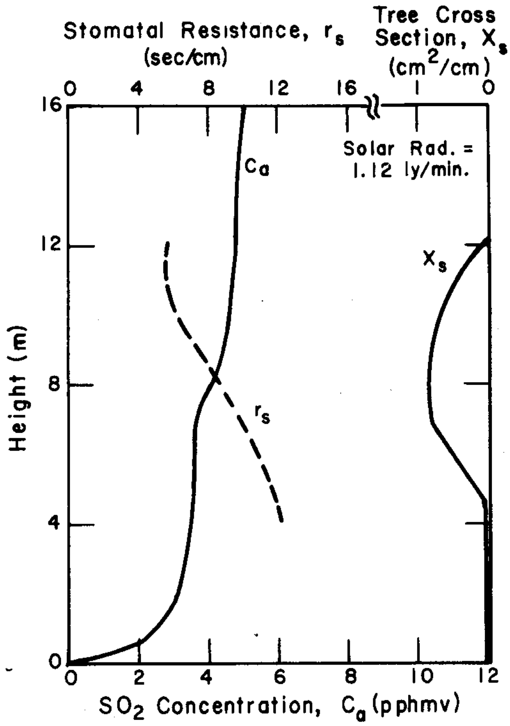


Figure 3.—The distribution of pollution concentration and related tree parameters at high solar radiation.

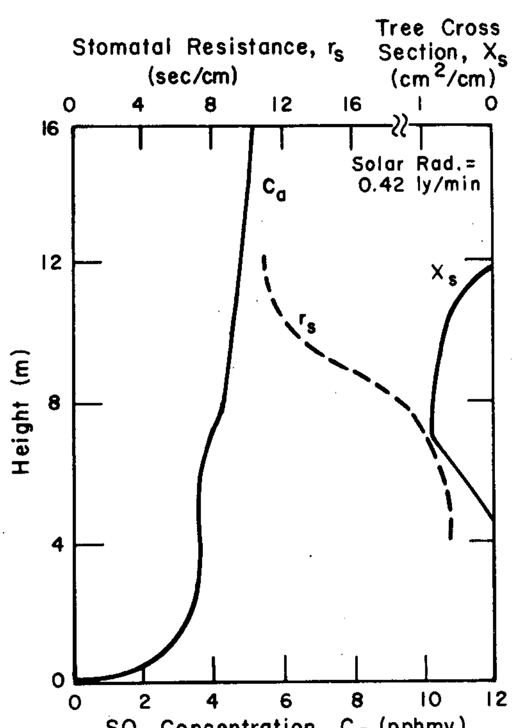


Figure 4.—The distribution of pollution concentration and related tree parameters at low solar radiation.

dioxide uptake reflects the effect of changing solar radiation and temperature on stomatal resistance and sulfur dioxide solubility. The seasonal pattern is affected by these variables and also by the seasonal change in day length and leaf area.

No experimental measurements have been taken under similar climatic and stand conditions, but the uptake rates compare well with those found in laboratory experiments. Table 2 compares the average daily uptake rates from the simulation with the laboratory data of Roberts (*1974*), and Bennett and Hill (*1973*). The results of Bennett and Hill are particularly interesting because an effort was made to duplicate field conditions. The simulated uptake appears to be an order of magnitude smaller than the experimental value. This can be explained on the basis of the high value of the internal diffusion resistance used in the simulation. However, it should be pointed out that the uptake per unit leaf area agrees quite well with the values found for tree species by Roberts, indicating that tree leaves may actually absorb sulfur dioxide more slowly than some other types of vegetation.

Although these results indicate that conifers have a potential for removing sulfur dioxide from the atmosphere, this potential may not be met if climatic conditions are unfavorable. Low light intensity or cold weather can cause stomatal closure and limit sulfur dioxide uptake, as demonstrated in figures 3 and 4. On the other hand, data collected by Martin and Barber (*1971*) clearly show that during periods when atmospheric conditions favor the deposition of dew, this surface water can be a sizable sink for transient absorption of sulfur dioxide.

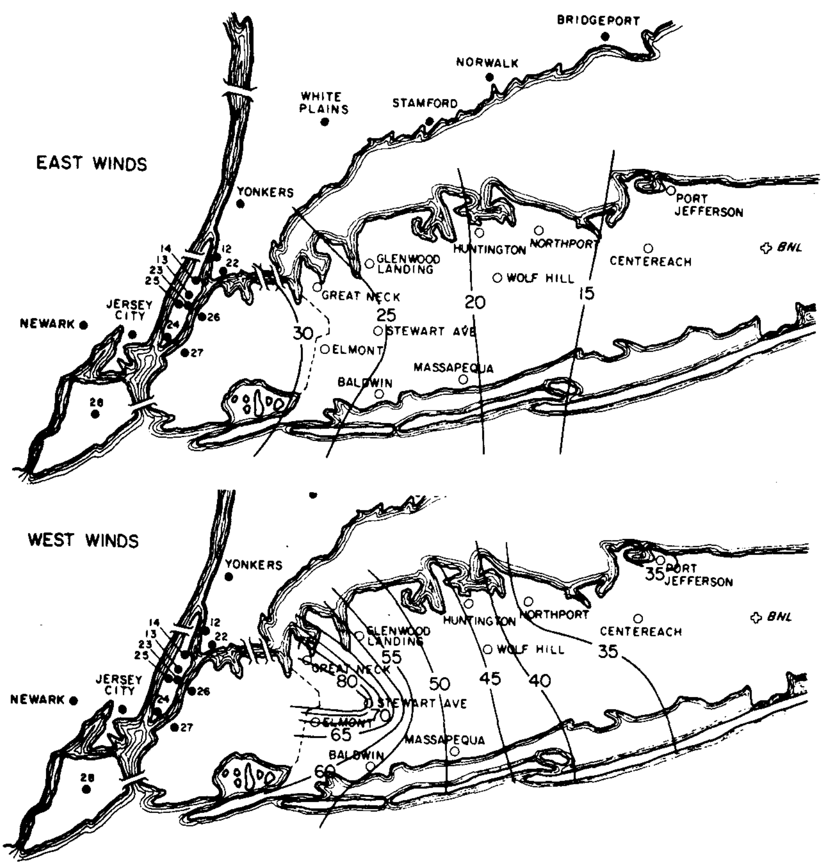
The results of these simulations or similar ones can be used to estimate the uptake of sulfur dioxide over a large area that has trees or crops as a major vegetative component of the landscape.

Table 2.—Comparison of model and experiments

Species	Uptake (kg/ha-hr-pphmv)	Source
Red maple	8.8 x 10^{-4}	Roberts (1974)
White birch	8.6 x 10^{-4}	
Sweetgum	7.4 x 10^{-4}	
White ash	4.6 x 10^{-4}	
Alfalfa	2.9 x 10^{-2}*	Bennett and Hill (1973)
	6.2 x 10^{-3}	
Loblolly pine	7.0 x 10^{-3}*	January simulation
	1.2 x 10^{-3}	
	9.8 x 10^{-3}*	July simulation
	9.8 x 10^{-4}	

*Based on ground-surface area; other values based on leaf-surface area.

Figure 5.—Mean annual isopleths of sulfur dioxide concentrations with west and east wind over Long Island, New York *(from Raynor et al. 1974)*.



This could be forests, parks, farms, or urban areas where the shade trees dominate the surface area. We have made calculations of this type, using the data of Raynor *et al. (1974)* for atmospheric sulfur dioxide concentrations on Long Island, New York (~3276 sq km). Figure 5, redrawn from their paper, shows the average concentrations under two different meteorological conditions. The weighted uptake, assuming the island is completely forested, is 54 metric tons per day for the east-wind case and 256 metric tons per day for the west-wind case, based on the summer values of the simulations shown above.

The sulfur dioxide released to the atmosphere by a large power plant (7,200 metric tons of coal consumed per day) is 280 metric tons per day based on Environmental Protection Agency emission factors (*EPA 1972*). It seems that absorption by vegetation over even large land areas is not significant compared to the output of large power plants. However, if an advanced pollution-abatement method such as catalytic conversion is used, the actual output will be closer to 28 metric tons per day. Under these conditions the forest could absorb a significant portion of the sulfur dioxide present from nine power plants when meteorological conditions are favorable.

Optimum management of forest buffers around urban or industrial areas will be complicated by the effects of diurnal and seasonal variation in absorption. Ideally the pollutant emission could be timed to periods of optimum absorption by the forest; however, in most cases this is not practical. The more attractive alternative seems to be the development of a forest type that has good absorption characteristics during most of the year. Year-round uptake may not be possible in all climates. In the southeastern United States it is possible to grow large areas of coniferous species that have good sulfur dioxide absorption characteristics throughout the year. In colder or drier climates, vegetation uptake may not be as suitable because the major type of vegetation is deciduous, and the conifers have very slow metabolic rates at temperatures below freezing.

Therefore it seems that practical use of forests for air-pollutant sinks must rely on a combination of the proper species grown in the proper climate, with delivery of the pollutants at concentrations and times that favor uptake. However, even under less-than-optimum conditions, forests play an important role in pollution abatement. If the inclusion of a park or natural area in an otherwise urbanized space will decrease sulfur dioxide concentration during half the days in the year, this may be a very desirable use of this space when considered as part of a multipurpose park system.

LITERATURE CITED

Bennett, Jesse, H. and A. Clyde Hill.
1973. ABSORPTION OF GASEOUS AIR POLLUTANTS BY A STANDARDIZED PLANT CANOPY. J. Air Pollut. Control Assoc. 23: 203-206.

Bennett, Jesse, H. and A. Clyde Hill.
1974. ACUTE INHIBITION OF APPARENT PHOTOSYNTHESIS BY PHYTOTOXIC AIR POLLUTANTS. *In* Air pollution effects on plant growth: 115-127. Am. Chem. Soc., Washington, D. C.

Businger, J. A., J. C. Wyngaard, Y. Izumi, and E. F. Bradley.
1971. FLUX-PROFILE RELATIONSHIPS IN THE ATMOSPHERIC SURFACE LAYER. J. Atmos. Sci. 28: 181-189.

Cionco, R. M.
1965. A MATHEMATICAL MODEL FOR AIR FLOW IN A VEGETATIVE CANOPY. J. Appl. Meteorol. 4: 517-522.

Environmental Protection Agency.
1972. COMPILATION OF AIR POLLUTION EMISSION FACTORS. EPA Off. Air Programs, Research Triangle Park, N. C.

Faller, N.
1972. ABSORPTION OF SULFUR DIOXIDE BY TOBACCO PLANTS DIFFERENTLY SUPPLIED WITH SULPHATE. *In* Isotopes and radiation in soil-plant relationships including forestry: 51-56. IAEA, Vienna.

Gaastra, P.
1959. PHOTOSYNTHESIS OF CROP PLANTS AS INFLUENCED BY LIGHT, CARBON DIOXIDE, TEMPERATURE AND STOMATAL DIFFUSION RESISTANCE. Meded. Landb. Hogesch. Wageningen. 58: 1-68.

Gresham, Charles A.
1972. THE EFFECT OF TEMPERATURE AND LIGHT ON THE DIFFUSION RESISTANCES OF LOBLOLLY PINE. Masters thesis, Duke Univ. Sch. For. Durham, N. C. 68 p.

Hales, Jeremy M., and Sue L. Sutter.
1973. SOLUBILITY OF SULFUR DIOXIDE IN WATER AT LOW CONCENTRATIONS. Atmos. Environ. 7: 997-1001.

Higgenbotham, Kenneth O.
1974. THE INFLUENCE OF CANOPY POSITION AND THE AGE OF LEAF TISSUE ON GROWTH AND PHOTOSYNTHESIS IN LOBLOLLY PINE. Ph.D. dissertation, Duke Univ. Dep. Bot. Durham, N. C. 248 p.

International Business Machines Corp.
1972. SYSTEM/360 CONTINUOUS SYSTEM MODELING PROGRAM USER'S MANUAL. IBM, White Plains, N. Y. 76 p.

Johnstone, H. E., and P. W. Leppla.
1934. THE SOLUBILITY OF SULFUR-DIOXIDE AT LOW PARTIAL PRESSURES. J. Am. Chem. Soc. 56: 2233-2238.

Martin, A., and F. R. Barber.
1971. SOME MEASUREMENTS OF LOSS OF ATMOSPHERIC SULPHUR DIOXIDE NEAR FOLIAGE. Atmos. Environ. 5: 345-352.

Monteith, J. L.
1965. EVAPORATION AND ENVIRONMENT. Symp. Soc. Exp. Biol. 19: 205-234.

Murphy, C. E., Jr., T. R. Sinclair, R. S. Kinerson, K. O. Higgenbotham, K. R. Knoerr, and B. R. Strain.
1974. MODELING THE PRIMARY PRODUCTIVITY PROCESS—A COORDINATED EFFORT AT AN INTENSIVE RESEARCH SITE. Simulation Councils Inc. Summer Computer Simul. Conf. Proc. 1974: 684-689. LaJolla, Cal.

Paulson, C. A.
1970. THE MATHEMATICAL REPRESENTATION OF WIND SPEED AND TEMPERATURE PROFILES IN THE UNSTABLE ATMOSPHERIC SURFACE LAYER. J. Appl. Meteorol. 9: 857-861.

Raynor, Gilbert S., Maynard E. Smith, and Irving A. Singer.
1974. METEOROLOGICAL EFFECTS ON SULFUR DIOXIDE CONCENTRATIONS ON SUBURBAN LONG ISLAND, NEW YORK. Atmos. Environ. 8: 1305-1320.

Roberts, Bruce R.
1974. FOLIAR SORPTION OF ATMOSPHERIC SULFUR DIOXIDE BY WOODY PLANTS. Environ. Pollut. 7: 133-139.

Sellers, William D.
1965. PHYSICAL CLIMATOLOGY. Univ. Chicago Press, Chicago. 272 p.

Sinclair, T. R.
1972. A LEAF PHOTOSYNTHESIS SUBMODEL FOR USE IN GENERAL GROWTH MODELS. Triangle Res. Site., EDFB, U.S.I.B.P., Memo Rep. 72-14, 14 p.

Smith, W. H.
1972. AIR POLLUTION — EFFECTS ON THE QUALITY AND RESILIENCE OF THE FOREST ECOSYSTEM. Annu. Meet. AAAS, Washington, D. C. 27 p.

Takeda, K.
1963. TURBULENCE IN PLANT CANOPIES. J. Agric. Meteorol. 20: 1-6.

Acknowledgments. The authors acknowledge the contributions of Dr. R. L. Barnes, School of Forestry, Duke University, for discussion of the metabolic absorption by trees, and Dr. M. M. Pendergast, E. I. du Pont de Nemours & Co., Savannah River Laboratory, for information about atmospheric dispersion of air pollutants.