MODELING THE EFFECTS OF URBAN VEGETATION ON AIR POLLUTION

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INTRODUCTION

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmospheric environment. Trees affect local air temperature by transpiring water through their leaves, by blocking solar radiation (tree shade), which reduces radiation absorption and heat storage by various anthropogenic surfaces (e.g., buildings, roads), and by altering wind characteristics that affect air dispersion. During the summertime, trees predominantly reduce local air temperatures, but may increase within- and below-canopy air temperature due to reduced turbulent exchange with above-canopy air (Heisler et al., 1995). Reduced air temperature due to trees can improve air quality because the emission of many pollutants and/or precursor chemicals are temperature dependent. Decreased air temperature can also reduce ozone (O_3) formation (Cardelino and Chameides, 1990).

Besides affecting air temperature, the physical mass, water transpiration, and thermal/radiative properties of trees can affect wind speed, relative humidity, turbulence, and surface albedo. In addition, trees affect surface roughness and consequently the evolution of the mixing-layer height, which in turn affects O_3 formation (Berman et al., in press). These changes in local meteorology can alter pollution concentrations in urban areas.

Trees remove gaseous air pollution primarily by uptake via leaf stomata, though some gases are removed by the plant surface (Smith, 1990). Once inside the leaf, gases diffuse into intercellular spaces and may be absorbed by water films to form acids or react with inner-leaf surfaces. Trees also remove pollution by intercepting airborne particles. Some particles can be absorbed into the tree (e.g., Zeigler, 1973), though most particles that are intercepted are retained on the plant surface. The intercepted particle often is resuspended to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall. Consequently, vegetation is only a temporary retention site for many atmospheric particles.

Emissions of volatile organic compounds (VOCs) by trees can contribute to the formation of O_3 and carbon monoxide (CO) (Brasseur and Chatfield, 1991). Because VOC

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emissions are temperature dependent and trees generally lower air temperatures, increased tree cover can lower overall VOC emissions and, consequently, O_3 levels in urban areas (Cardelino and Chameides, 1990).

Trees reduce building energy use by lowering temperatures and shading buildings during the summer, and blocking winds in winter (e.g., Heisler, 1986). However, they also increase energy use by shading buildings in winter, and may increase or decrease energy use by blocking summer breezes. Thus, proper tree placement near buildings is critical to achieve maximum building energy conservation benefits.

When building energy use is lowered, pollutant emissions from power plants are also lowered. While lower pollutant emissions generally improve air quality, lower NO_x emissions, particularly ground-level emissions, may lead to a local increase in O_3 concentrations under certain conditions due to NO_x scavenging of O_3 (Rao and Mount, 1994). The cumulative and interactive effects of trees on meteorology, pollution removal, and VOC and power plant emissions determine the overall impact of trees on air pollution.

Modeling Urban Vegetation Effects on Air Quality

Research integrating the cumulative effects of urban vegetation on air quality, particularly ozone, is limited. Cardelino and Chameides (1990) modeled vegetation effects on ozone concentrations in the Atlanta region using the OZIPM4 model. The study's primary focus was on the interaction of VOC emissions and altered air temperatures, and revealed that a 20 percent loss in the area's forest due to urbanization could have lead to a 14 percent increase in O_3 concentrations for June 4, 1984. Although there were fewer trees to emit VOCs, an increase in Atlanta's air temperatures due to the urban heat island, which occurred concomitantly with tree loss, increased VOC emissions from the remaining trees and anthropogenic sources, and altered O_3 photochemistry such that concentrations of O_3 increased.

A model simulation of California's South Coast Air Basin suggests that the air quality impacts of increased urban tree cover may be locally positive or negative. The net basin-wide effect of increased urban vegetation is a decrease in ozone concentrations if the additional trees are low VOC emitters (Taha, 1996). This study used the Colorado State University Mesoscale (CSUMM) and Urban Airshed Models (UAM-IV), and accounted for vegetation temperature reduction effects on altered chemical reaction rates, reduced temperature dependent biogenic VOC emissions, and changes in the depth of the mixed layer. It also accounted for increased pollution deposition and possible increased VOC emissions due to increased vegetative cover.

This paper is an overview of a current research project, funded by the National Urban and Community Forestry Advisory Council, that is investigating the cumulative and interactive effects of altered meteorology, dry deposition, VOC emissions, and power plant emissions, due to increased and decreased urban tree cover, on local and regional ozone concentrations. This study is focusing on four cities (Baltimore, MD; Boston, MA; New York, NY; and Philadelphia, PA) and the total urban megalopolis of Washington, DC, to Boston, MA. A new Urban Forest Effects (UFORE) model is also detailed, and preliminary results of pollution removal by trees in Philadelphia are presented.

MODELING METHODS

To determine base conditions in each city, approximately 210 stratified (by land use), random, 0.04-ha ground plots were measured to determine vegetative and artificial surface parameters. From these data, leaf-surface area and biomass were calculated (Nowak, 1996). Aerial photographs and satellite imagery were analyzed to determine the amount of tree cover and potential space for tree cover in the future. To model the effects of altered urban tree cover on ozone, three scenarios are being modeled: 1) Base Case: existing vegetation configuration, 2) No Tree: all tree cover removed and replaced with grass, and 3) High Tree: all non-tree cover grass space filled with trees.

To model the effects of altered tree cover on meteorological conditions, the Pennsylvania State University / National Center for Atmospheric Research Mesoscale Model 5 (MM5) is being used (Dudhia, 1993). To model the effects of urban trees on ozone removal (dry deposition), VOC emissions, and power plant emissions an Urban Forest Effects (UFORE) model was developed. Results of changes in meteorological conditions, deposition velocities, VOC emissions and power plant emissions due to altered urban tree cover will be input into the SARMAP air quality model (SAQM) (Pleim et al., 1991) to quantify the overall effect of altered tree cover on local and regional ozone concentrations for the ozone episode period of July 13-15, 1995. Project completion is expected in December 1997. Recently completed results revolve around the completion of the UFORE model, in particular, the dry deposition component.

The UFORE model currently has five modules in development or completed. UFORE-A: Anatomy of the Urban Forest, quantifies urban vegetation and artificial surface characteristics (e.g., species composition, tree condition, leaf surface area and biomass, tree biomass, ground cover distribution, artificial surface characteristics) by land use type based on field data inputs. UFORE-B: Biogenic VOC Emissions, calculates hourly isoprene, monoterpene, and other VOC (OVOC) emissions based on species leaf biomass calculations (from UFORE-A), National Climatic Data Center (NCDC) hourly weather data, base VOC emission factors, and emission temperature and light correction factors (Guenther et al., 1994). UFORE-C: Carbon Storage and Sequestration, determines the amount of carbon currently stored and annually sequestered by urban trees within each land use type (based on UFORE-A inputs). UFORE-D: Dry Deposition of Air Pollutants, calculates the hourly dry deposition of ozone, sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide, and daily deposition of particulate matter less than 10 microns (PM10) to tree canopies throughout the year based on tree cover data, NCDC weather data, and U.S. Environmental Protection Agency (EPA) pollution concentration monitoring data. UFORE-E: Energy Conservation and Power Plant Emission Effects, computes the effect of trees on local building energy use (based on UFORE-A data and published tree-energy effects data) and the consequent effect on local power plant emissions. The UFORE model is programmed in SAS. One of the most detailed modules is UFORE-D, which accounts for the interaction of the hourly variation in tree transpiration and pollution deposition (based on local meteorological data) and the hourly pollutant concentration data.

UFORE -D: Dry Deposition of Air Pollutants

In UFORE-D, the pollutant flux (F) is calculated as the product of the deposition velocity (V_d) and the pollutant concentration (C):

$$F\ (g\ m^{-2}\ s^{-1}) = V_d\ (m\ s^{-1}) \times C\ (g\ m^{-3}) \quad (1)$$

Deposition velocity is calculated as the inverse of the sum of the aerodynamic (R_a), quasi-laminar boundary layer (R_b) and canopy (R_c) resistances (Baldocchi et al., 1987):

$$V_d = (R_a + R_b + R_c)^{-1} \quad (2)$$

Hourly meteorological data from the NCDC are used in estimating R_a and R_b. The aerodynamic resistance is calculated as (Killus et al., 1984):

$$R_a = u(z)\, u_*^{-2} \tag{3}$$

where u(z) is the mean wind speed at height z (m s^{-1}) and u_* is the friction velocity (m s^{-1}).

$$u_* = (k\, u\, (z\text{-}d))\, [\ln((z\text{-}d)\, z_o^{-1}) - \psi_M((z\text{-}d)\, L^{-1}) + \psi_M(z_o\, L^{-1})]^{-1} \tag{4}$$

where k = von Karman constant, d = displacement height (m), z_o = roughness length (m), ψ_M = stability function for momentum, and L = Monin-Obuhkov stability length. L was estimated by classifying hourly local meteorological data into stability classes using Turner classes (Panofsky and Dutton, 1984) and then estimating 1/L as a function of stability class and z_o (Zannetti, 1990). When $L<0$ (unstable) (van Ulden and Holtslag, 1985):

$$\psi_M = 2 \ln[0.5(1+X)] + \ln[0.5(1+X^2)] - 2\tan^{-1}(X) + 0.5\pi \tag{5}$$

where $X = (1 - 28\, z\, L^{-1})^{0.25}$ (Dyer and Bradley, 1982). When $L>0$ (stable conditions):

$$u_* = C_{DN} u\{0.5 + 0.5[1-(2u_o/(C_{DN}^{1/2} u))^2]^{1/2}\} \tag{6}$$

where $C_{DN} = k\,(\ln(z/z_o))^{-1}$; $u_o^2 = (4.7\, z\, g\, \theta_*)\, T^{-1}$; $g = 9.81$ m s^{-2}; $\theta_* = 0.09\,(1 - 0.5\, N^2)$; T = air temperature (K°); and N = fraction of opaque cloud cover (Venkatram, 1980; U.S. EPA, 1995). Under very stable conditions, u_* was calculated by scaling actual wind speed with a calculated minimum wind speed based on methods given in U.S. EPA (1995).

The quasi-laminar boundary-layer resistance was estimated as (Pederson et al., 1995):

$$R_b = 2(Sc)^{2/3}\,(Pr)^{-2/3}\,(k u_*)^{-1} \tag{7}$$

where k = von Karman constant, Sc = Schmidt number, and Pr is the Prandtl number.

In-leaf, hourly tree canopy resistances for ozone, sulfur dioxide, and nitrogen dioxide were calculated based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi et al., 1987; Baldocchi, 1988). Canopy resistance (R_c) has three components: stomatal resistance (r_s), mesophyll resistance (r_m), and cuticular resistance (r_t), such that:

$$1/R_c = 1/(r_s + r_m) + 1/r_t \tag{8}$$

Mesophyll resistance was set to zero for O_3 and SO_2 (Wesely, 1989), and 600 s m^{-1} for NO_2, to account for the difference between transport of water and NO_2 in the leaf interior and to bring the computed deposition velocities in the range typically exhibited for NO_2 (Lovett, 1994). Base cuticular resistances were set at 8,000 m s^{-1} for SO_2, 10,000 m s^{-1} for O_3, and 20,000 m s^{-1} for NO_2 to account for the typical variation in r_t exhibited among the pollutants (Lovett, 1994).

Hourly inputs to calculate canopy resistance are photosynthetic active radiation (PAR; μE m^{-2} s^{-1}), air temperature (K°), wind speed (m s^{-1}), u_* (m s^{-1}), carbon dioxide concentration (set to 360 ppm), and absolute humidity (kg m^{-3}). Air temperature, wind speed, u_*, and absolute humidity are measured directly or calculated from measured hourly NCDC meteorological data. Total solar radiation is calculated based on the National Renewable Energy Laboratory Meteorological / Statistical Solar Radiation Model (METSTAT) with inputs from the NCDC data set (Maxwell, 1994). PAR is calculated as 46 percent of total solar radiation input (Monteith and Unsworth, 1990).

As carbon monoxide and particulate matter removal by vegetation is not directly related to transpiration, R_c for CO was set to a constant for in-leaf season (50,000 s m^{-1}) and leaf-off season (1,000,000 s m^{-1}) based on data from Bidwell and Fraser (1972). For particles, the deposition velocity (based on average V_d from the literature) was set at 0.0064 m s^{-1} for the in-leaf season and 0.0014 m s^{-1} for the leaf-off season, both of which incorporate a 50 percent resuspension rate of particles back to the atmosphere (Zinke, 1967).

The model uses an urban tree leaf area index of 6, and a distribution of 90 percent deciduous and 10 percent coniferous leaf surface area (Nowak, 1994). Local leaf-on and leaf-off dates are input into the model so that deciduous tree transpiration and related pollution deposition are limited to the in-leaf period, and seasonal variation in removal can be illustrated for each pollutant. Particle collection and gaseous deposition on deciduous trees in winter assumed a surface-area index for bark of 1.7 (m^2 of bark per m^2 of ground surface covered by the tree crown) (Whittaker and Woodwell, 1967). To limit deposition estimates to periods of dry deposition, deposition velocities were set to zero during periods of precipitation.

Hourly pollution concentrations (ppm) for gaseous pollutants were obtained from the EPA. Hourly ppm values were converted to μg m^{-3} based on measured atmospheric temperature and pressure (Seinfeld, 1986). Average daily concentrations of PM10 (μg m^{-3}) also were obtained from the EPA.

Average hourly pollutant flux (g m^{-2} of tree canopy coverage) among the pollutant monitor sites was multiplied by city tree canopy coverage (m^2) to estimate total hourly pollutant removal by trees across the city. Bounds of total tree removal of O_3, NO_2, SO_2, and PM10 were estimated using the typical range of published in-leaf dry deposition velocities (Lovett, 1994).

Monetary value of pollution removal by trees is estimated using the median externality values for the United States for each pollutant. The externality values are: NO_2 = \$6,750 t^{-1}, PM10 = \$4,500 t^{-1}, SO_2 = \$1,650 t^{-1}, and CO = \$950 t^{-1} (Murray et al., 1994). Externality values for O_3 were set to equal the value for NO_2.

To approximate boundary-layer heights in the study area, mixing-height measurements from a nearby station were used. Daily morning and afternoon mixing heights were interpolated to produce hourly values using the EPA's PCRAMMIT program (U.S. EPA, 1995). Minimum boundary-layer heights were set to 150 m during the night and 250 m during the day based on estimated minimum boundary-layer heights in cities. Hourly mixing heights (m) were used in conjunction with pollution concentrations (μg m^{-3}) to calculate the amount of pollution within the mixing layer (μg m^{-2}). This extrapolation from ground-layer concentration to total pollution within the boundary layer assumes a well-mixed boundary layer. The amount of pollution in the air was contrasted with the amount of pollution removed by trees to calculate the relative effect of trees in reducing local pollution concentrations:

$$E = R\,(R+A)^{-1} \qquad (9)$$

where E = relative reduction effect (%); R = amount removed by trees (kg); A = amount of pollution in the atmosphere (kg).

POLLUTION REMOVAL BY TREES IN PHILADELPHIA, PA.

The City of Philadelphia (362 km^2) was analyzed using UFORE-D for 1994. Within Philadelphia there are 5 O_3, 6 SO_2, 3 NO_2, 4 CO, and 7 PM10 monitors. Weather data from the Philadelphia airport and boundary-layer height measurements from Sterling, VA, were input into the model. Overall tree cover in Philadelphia is 21.6 percent. UFORE-D calculations predicted that total air pollution removal by Philadelphia's trees was 1,084 metric tons in 1994 with an estimated value of \$5.4 million (Table 1). Total removal and percent air-quality improvement exhibit diurnal and seasonal patterns based on vegetation and meteorological conditions, and atmospheric pollution concentration (Table 2). Average percent air-quality

Table 1. UFORE-D estimates of total dry deposition to trees, associated monetary value, and average in-leaf daytime deposition velocities (V_d), for carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and particulate matter less than 10 microns (PM10) in Philadelphia, PA, in 1994. Number in parentheses represent expected range based on the typical range of V_d found in the literature (Lovett, 1994).

Pollutant	Total Deposition (t)	Value ($ x 1000)	V_d (m s^{-1})
PM10[a]	418 (160 - 789)	1,884 (723 - 3,555)	0.0064
O_3	306 (89 - 418)	2,069 (604 - 2,820)	0.0056
NO_2	169 (86 - 209)	1,138 (581 - 1,410)	0.0037
SO_2	163 (82 - 256)	270 (136 - 423)	0.0055
CO	28	27	0.00002
Total	1,084 (445 - 1700)	5,388 (2,071 - 8,235)	

[a] Assumes 50% resuspension of particles

Table 2. Monthly pollution removal (t) attributed to trees in Philadelphia, PA (1994).

	Month											
Pollutant	J	F	M	A	M	J	J	A	S	O	N	D
PM10	12	11	12	28	59	66	62	64	54	21	14	16
O_3	3	4	4	18	48	64	68	49	36	7	3	3
NO_2	5	6	6	12	23	27	22	23	22	9	6	6
SO_2	4	4	4	9	24	28	28	27	22	7	4	4
CO	0[a]	0[a]	0[a]	2	5	5	4	5	5	2	0[a]	0[a]

[a] 0.3 t

improvement due to dry deposition to trees during the in-leaf season for the entire city was: PM10 = 0.72%, O_3 = 0.29%, SO_2 = 0.29%, NO_2 = 0.2%, CO = 0.002%. Average air-quality improvement during the in-leaf season was highest just after sunrise when boundary layer heights are still relatively low. Maximum air-quality improvement for the city was about 3 percent for a one-hour period for SO_2, O_3, and PM10. In areas with complete (100 percent) tree cover, air-quality improvement may occasionally reach 13 percent for an hour period depending on boundary-layer height.

The next phase in UFORE-D development is to integrate all urban surfaces together in an urban deposition model. This model will account for the diurnal and seasonal deposition to trees, shrubs, grasses, and other plants, and will include deposition to the myriad of artificial surfaces encountered in urban areas (e.g., buildings, roads, etc.). Model results in urban areas are being validated through eddy-flux measurements that were made in Chicago, IL (King et al., 1995). Preliminary validation of the model results based on published field measurements reveals that model predictions are within the typical range of deposition values for all pollutants. However, mesophyll resistance was increased for NO_2 to account for the difference between the transport of water and NO_2 in the leaf interior, and to bring the estimated NO_2 deposition values within the measured values found in the literature (Lovett, 1994). Future research needs to investigate mechanisms by which gas deposition is different from the resistance to water efflux (after adjustment for the relative diffusivities of water and the pollutant gas), particularly for NO_2.

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DISCUSSION

R. BORNSTEIN: Have you included feedback's associated with the effects of trees on surface albedo, etc.?

D. J. NOWAK: Yes, they are included in the Mesoscale Model 5 (MM5) simulations.

D. FISH: Do you know enough about deposition of pollutants onto buildings and roads to be able to say whether trees have a positive or negative effect on air pollution?

D. J. NOWAK: Literature is being compiled on deposition velocities to various artificial surfaces. This information will be incorporated as part of an urban deposition model with results being input into the SARMAP air quality model to help determine whether the overall impact of urban trees is either positive or negative.

R. SAN JOSE: Have you compared the effects due to the ozone removal by deposition and the ozone production due to isoprene and monoterpene emissions due to urban vegetation?

D. J. NOWAK: Though this has not been done yet, project results will allow for a comparison of ozone removal due to deposition with the ozone effects from volatile organic compound emissions and the effect of the trees on local meteorology.