Reprinted from the Preprint Volume of the Ninth Joint Conference on the Applications of Air Pollution Meteorology with the Air and Waste Management Association, 28 January 1996-2 February 1996. Atlanta, GA. Published by the American Meteorological Society, Boston, Mass.

P1.3 "BACT" ANALYSIS: ARE THERE COST EFFECTIVE AIR QUALITY BENEFITS FROM TREES ?

E. Gregory McPherson*, James R. Simpson, Klaus I. Scott

USDA Forest Service, Pacific Southwest Research Station
Davis, California

1. INTRODUCTION

Trees absorb gaseous pollutants through leaf stomata and can bind or dissolve water soluble pollutants onto moist leaf surfaces. Tree canopies also intercept particulates and reduce local air temperatures. Urban trees may reduce ambient air ozone concentrations, either by direct absorption of ozone or other pollutants such as NO_2, or by reducing air temperatures, which reduces hydrocarbon emission and ozone formation rates (Cardelino and Chameides 1990). On the other hand, biogenic hydrocarbon emissions from trees may play a role in ozone formation. The role of trees in air quality has become coupled with concern over the costs and benefits of large-scale urban tree planting programs (Corchnoy et al. 1992). For example, Sacramento Shade, a partnership between the Sacramento Municipal Utility District (SMUD) and the non-profit Sacramento Tree Foundation, is assisting residents plant about 50,000 trees annually near homes to reduce air conditioning demand. It is one of SMUD's most cost-effective energy efficiency programs. An additional benefit of shade tree programs is lowered CO_2 emissions from power plants and increased storage of atmospheric CO_2 in tree biomass. However, their 10 year goal of planting 500,000 new trees has air quality managers concerned about the impact of hydrocarbon emissions on ozone levels in the country's fifth smoggiest region.

Air quality management districts provide pollution abatement credits to businesses and institutions by permitting the use of controls or processes, provided they are technically feasible and cost effective, based upon guidelines in Best Available Control Technology (BACT) manuals. Typically BACT analysis is applied to stationary sources, but we apply it here to determine if a large-scale urban tree planting like Sacramento Shade can be a cost effective means to improve air quality.

**Corresponding author address:* E. Gregory McPherson, USDA Forest Service, Western Center for Urban Forest Research & Education, c/o Dept. of Environmental Horticulture, University of California, Davis, CA 95616-8587.

2. METHODS

2.1 Tree Growth and Mortality

We assumed annual growth followed an S-shaped curve: slow at first, most rapid during the middle years, and slowing as the tree reaches mature size 50 years after planting. To estimate mature tree size we recorded tree height, crown spread, and trunk diameter at breast height (d.b.h.) of 12 Modesto ash (*Fraxinus velutina* Modesto) planted in front yards during 1948. These dimensions averaged 16 m (52 ft), 15 m (48 ft), and 58 cm (23 in), respectively. Leaf surface area (LA) for the "typical" large-growing deciduous shade tree was calculated as $LA = LAI \times CP$ where the LAI (leaf area index) is 5 (Nowak 1994a) and CP (crown projection) is area under the tree crown.

Mortality rates have been reported for street trees, but not residential yard trees (Miller and Miller 1991, Dawson and Khawaja 1985). We assumed that 100 trees were planted, 21 died during the first five year establishment period, and one tree died every other year thereafter. Thus, 67 trees survived 30 years after planting.

2.2 Deposition

Dry deposition to urban trees was estimated on a per-tree basis. The hourly deposition to a tree is expressed as the product of a deposition velocity $V_d = 1/(R_a+R_b+R_c)$, a pollutant concentration C, a leaf surface area and a time step. Hourly deposition velocities for each pollutant were calculated using estimates for the resistances R_a, R_b, and R_c. Hourly meteorological data for wind speed, solar radiation and precipitation from a California Department of Water Resources monitoring site located in Sacramento County, together with nighttime three-hourly cloud cover data from Executive Airport were used to estimate the aerodynamic and quasi-boundary layer resistances R_a and R_b. R_a and R_b were estimated for each hour throughout a "base year" (1990) using formulations from the Urban Airshed Model (Killus et al. 1984, Nowak 1994b).

Canopy resistances R_c for individual pollutants were based on averages taken from literature values for both forests and individual trees (Nowak 1994b). Hourly R_c estimates were categorized into in-leaf season (March 15 through November 15, based on local foliation periods), daytime, and nighttime. Canopy resistances for particles could not be found in the literature. A substitute R_c was estimated based upon an average deposition velocity minus an average R_a and R_b for Sacramento. Average daytime and nighttime canopy resistance values (sec cm^{-1}) were: NO_2 (3.01, 7.54), O_3 (1.74, 17.2), SO_2 (1.87, 9.54), PM_{10} (0.74, 0.74).

The hourly canopy resistances were combined with R_a and R_b to estimate hourly deposition velocities for each pollutant. Fifty percent of deposited particulate matter was assumed to be resuspended. Hourly pollutant depositions were then summed to get monthly and annual pollutant depositions for each year.

2.3 Pollutant Concentrations

Hourly concentrations for NO_2, O_3, SO_2 (ppm) and PM_{10} (µg/m^3) were obtained from the USEPA AIRS data base for 1990 for a monitoring station located in a residential neighborhood in Sacramento. The station monitors for air pollutant concentrations representative of areas of high population density, at spatial scales of up to 4 km (ARB 1994).

Pollutant concentrations in Sacramento in 1990 were typical of concentrations for the period 1989 to 1992. For the in-leaf season, hourly O_3 concentrations averaged 0.032 ppm. Average hourly concentrations were highest in July (0.039 ppm) and August (0.034 ppm) and lowest in October (0.026 ppm) and November (0.023 ppm). Peak concentrations occurred between 11 AM and 3 PM. In Sacramento County the 0.12 ppm hourly National Ambient Air Quality Standard (NAAQS) for ozone was exceeded 15 times between June and September. The average hourly NO_2 concentrations were highest in November (0.090 ppm) and the in-leaf season average hourly concentration was 0.015 ppm. The season average hourly SO_2 concentration was 0.001 ppm.

2.4 Biogenic Hydrocarbon Emissions

Biogenic hydrocarbon (HC) emissions (sometimes called reactive organic carbon or ROC) were also estimated on a per-tree basis. The hourly emission of ROC (g) from a tree is expressed as a product of a base emission rate EF (µg carbon g^{-1} leaf biomass hr^{-1}), a leaf biomass factor BF (g leaf biomass m^{-2} leaf area), an environmental adjustment factor F(S,T) and a leaf surface area (LA) (m^2) (Pierce et al. 1990). We estimate biogenic carbon emitted as isoprene, using a base emission rate of 20 µg HC g^{-1} leaf biomass hr^{-1}. The leaf biomass factor for *Fraxinus* was BF = 84.03 g leaf biomass m^{-2} leaf area (pers. comm., David Nowak, USDA Forest Service, 1994).

The environmental adjustment factor F(S,T) for isoprene emission is a function of solar radiation (S) and temperature (T). In natural forests solar radiation and leaf temperature vary through the depth of the canopy layer. However, profiles of solar radiation and leaf temperature within urban forest canopies are not well known. In our estimates of biogenic hydrocarbon emissions we assumed all leaves were in full sunlight during the day and that leaf temperature was equal to the air temperature. Hourly emissions were summed to get monthly and annual emissions.

2.5 Cost Effectiveness Analysis Procedure

A pollution control technology is cost effective if the cost of controlling one ton of air pollutant is less than the maximum cost specified in the BACT policy document. Control costs for Sacramento are listed per kg as: \$19.29 for ROC (\$17,500/ton), \$27.01 for NO_2 (\$24,500/ton), \$4.15 for PM_{10} (\$10,600/ton), and \$11.68 for SO_2 (\$18,300/ton) (SMAQMD 1993). No cost is listed for ozone because it is formed in the atmosphere and not directly emitted. Because programs to reduce ozone are increasingly aimed at reducing NO_2, the control price for NO_2 was applied to ozone. If the maximum control cost *MCC* is greater than the total annual control cost *TAC* a control is cost effective. MCC is estimated as

$$MCC = \frac{\sum_{k=1}^{n}\sum_{j=1}^{5}(c_j \times fc_j)}{n}$$

where c_j is the annual amount of pollution deposition or emission for pollutant species j, fc_j is the control cost per pollutant species, and pollutant uptake or emission is calculated for each year k to year n (30). *TAC* is estimated as

$$TAC = CRC + MRC$$

The capital recovery cost *CRC* is the uniform end-of-year payment necessary to repay the investment (*P*) in *n* years (30) with interest rate *I* (10%) where:

$$CRC = CRF \times P$$

and the cost recovery factor *CRF* is

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

The maintenance recovery cost *MRC* is the uniform annual payment necessary to repay the present value of 30-year tree maintenance costs (*M*) with an interest rate *I* (10%) where:

$$MRC = CRF \times M$$

and

$$M = \sum_{k=1}^{n} \frac{m_k}{(1+i)^k}$$

where m_k is the future value of total annual tree care costs for each year *k* to year *n* (30).

Tree planting and care costs were obtained from a survey of local garden centers and arborists. Costs were estimated for planting, removal of dead trees and stumps, pruning, and irrigation water. Although additional costs could accrue (e.g., pest and disease control), they are likely to be small if trees are judiciously selected and located.

A planting cost of $45 per tree (19 l [5 gal] size) for 100 trees was assumed. This price is midway between the likely range of $25 to $65. Trees dying during the 5-year establishment period were assumed to be removed by the resident at no cost. Removal costs for the remaining 13 trees ranged from $150 to $700 for trees between 5.6 and 40.6 cm (2.2-16 in) d.b.h. Based on survey results, stumps of every other dead tree were removed at a price of $1.57 per cm d.b.h. ($4/inch). Pruning of young trees was assumed to be done by the residents. We conservatively estimated pruning costs at $500 per tree for 50 percent of the 69 trees projected to be alive 25 years after planting. Height and d.b.h. of these 25 year old trees were estimated as 12.5 m (41 ft) and 33 cm (13 in).

Irrigation water costs were calculated for the first 10 years, assuming that thereafter trees would utilize existing water sources. Most trees are likely to be planted in turf and other irrigated areas where they can harvest surplus water and their shade can reduce the irrigation demand of nearby understory plants. Annual irrigation water use IWU (m^3) was estimated as:

$$IWU = (ET_o - P) \times (K \times CP \times \frac{1}{H})$$

where:
ET_o = reference evapotranspiration (m),
P = precipitation (m),
K = crop coefficient,
CP = crown projection (m^2),
H = irrigation efficiency (%)

Net evaporative demand in Sacramento was calculated using historic precipitation and ET_o data (NOAA 1990, Snyder et al. undated). Values of K and H were 0.5 and 0.7, respectively. These values are characteristic of tree species requiring moderate amounts of water in a turf landscape that is efficiently irrigated with automatic sprinklers (McPherson 1991). The City of Sacramento charges residents $0.19 m^{-3} ($0.54 · 100 ft^{-3}) for water delivered in 1995 (pers. communication, Phillip McAvoy, Department of Utilities, 1995).

3. RESULTS

Leaf surface area 30 years after planting was estimated to be 502 m^2 (5,403 ft^2) per tree and averaged 181 m^2 (1,949 ft^2) over the 30 years. When tree mortality is incorporated the average annual leaf surface area was 129 m^2 (1,383 ft^2) per tree planted.

3.1 Deposition and Emission

Throughout the study period, pollutant removal was greatest for ozone and PM_{10} (Figure 1). Ozone deposition was nearly five times greater than that for NO_2. SO_2 deposition was the smallest of the four pollutants, due to low ambient concentrations throughout the in-leaf season.

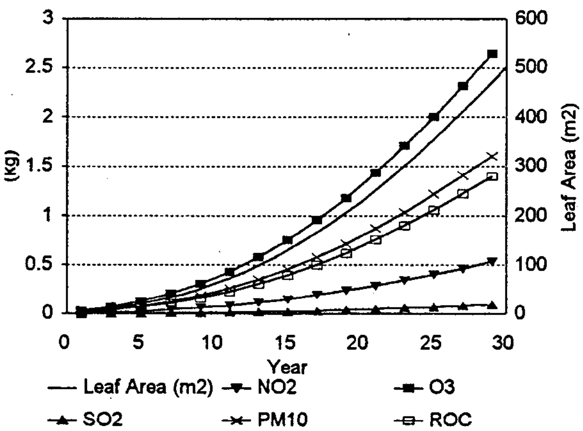

Figure 1. Estimated annual pollutant uptake and emission for a healthy tree.

By year 30, the estimated annual deposition for ozone was 2.73 kg; for PM_{10} 1.65 kg; for NO_2 0.55 kg and SO_2 0.10 kg (Figure 1). Annual biogenic carbon emission for year 30 was approximately 1.44 kg. During year 30, peak total monthly deposition for ozone occurred in July (0.47 kg) and August (0.42 kg), for NO_2 in August (0.07 kg) and October (0.12 kg), for SO_2 in April (0.08 kg) and for PM_{10} in September (0.23 kg) and October (0.32 kg). Peak total monthly biogenic carbon emissions for year 30 were in July and August (0.32 kg). Minimum monthly depositions during year 30 occurred in October for ozone (0.29 kg), in May for NO_2 (0.07 kg), in June for PM_{10} (0.09 kg), and in September for SO_2 (0.002 kg).

3.2 Cost Effectiveness

The planting cost for 100 trees was estimated to be $4,500. The cost recovery factor (*CRF*) and capital recovery cost (*CRC*) for planting were 10.6 percent and $477.36, respectively. The total present value of tree maintenance costs was estimated as $2,771.17 and the maintenance recovery cost (*MRC*) was $293.96. Maintenance costs were quite variable. The total future value of pruning ($17,250) and tree removal ($5,100) costs were greatest, while costs were least for irrigation water ($583) and stump removal ($216). The total annual cost (*TAC*), or uniform payment necessary to repay planting and maintenance costs over 30 years with an interest rate of 10 percent, was estimated as $771.32 (*CRC* + *MRC*).

TABLE 1
Average Annual Pollution Emission, Uptake, and Costs

Pollutant	Amount kg	Amount lb	fc^a $/kg	Total Cost $	$/yr/tree planted
ROC emitted	39.9	88.0	-19.29	(770)	-7.70
O_3 uptake	69.8	153.9	27.01	1,885	18.85
NO_2 uptake	14.0	30.9	27.01	378	3.78
PM_{10} uptake	39.5	87.1	4.15	462	4.62
SO_2 uptake	2.5	5.5	11.68	50	0.50
Net	85.9	189.4		2,005	20.05

[a] Maximum control costs for each pollutant.

The deciduous trees were estimated to emit 40 kg (88 lb) of ROC per year on average, at an annual cost of $770 (Table 1). Deposition of all other pollutants totaled 125.8 kg (277 lb), for an annual benefit of $2,775. The net pollution mitigation benefit, or *MCC* was estimated as $2,005.41. The hypothetical tree planting is cost effective because *MCC* is greater than *TAC*. The difference between *MCC* and *TAC* is $1,234.09 and the benefit-cost ratio is 2.6.

4. CONCLUSIONS AND LIMITATIONS OF THE STUDY

These findings suggest that a large-scale residential yard tree planting program such as Sacramento Shade may produce cost effective air quality benefits, as well as conserving electricity for air conditioning. Developers are now required to mitigate future air quality impacts of new building. Their investment in the planting and care of trees may result in cost effective mitigation of air quality impacts from new development, as well as add value to their properties. Although trees will not be a panacea for the region's air quality problems, they have potential to provide net benefits.

There are numerous limitations to this analysis. These limitations include little data on urban tree deposition velocities, tree health, growth, and survival; minimal research on pollution deposition in urban areas; extrapolation of work in chambers and forest stands to relatively open-grown urban trees; lack of consideration of tree configuration and local meteorology; and little knowledge about the relative ability of different tree species to intercept particulates and absorb gaseous pollutants, or their tolerance to air pollution stress. Moreover, our analysis occurs at a small scale without consideration of regional photochemical and meteorological processes. There is need for application of more sophisticated models (Sailor, 1995) and complementary field research to better understand the net effects of urban vegetation.

Nevertheless, this research builds on previous work by estimating the economic value of vegetation impacts on air quality. It is one of the first studies that accounts for both biogenic hydrocarbon emissions and ozone uptake by trees. It considers the 30 year stream of benefits and costs associated with an aging urban forest planting, whereas previous studies have been limited to periods of a year or less. Finally, by applying the BACT analysis it places urban forestry within the regulatory framework of air resource managers. With further quantification it will be possible to more precisely determine how investments in urban forestry impact air quality, human health, and health care costs.

4.1 Acknowledgments

Dr. David Nowak (USDA Forest Service), Mark Ott, Ron Maertz, and Brian Krebs (of SMAQMD) provided data and helpful reviews of earlier versions of this manuscript. Coe Owen (USEPA) and Jim Goodridge (Cal. Dept. Of Water Resources) supplied air pollutant and meteorological data.

4.2 References

Air Resources Board, 1994: California state and local air monitoring network plan. TSD94-001, California Environmental Protection Agency, Sacramento, CA.

Cardelino, C.A. and W.L. Chameides, 1990: Natural hydrocarbons, urbanization and urban ozone. *Journal of Geophysical Research*, 95,13971-13979.

Corchnoy, S.B., Arey, J. and R. Atkinson, 1992: Hydrocarbon emissions from twelve urban shade trees of the Los Angeles, California, air basin. *Atmospheric Environment*, 26B,(3), 339-348.

Dawson, J. O. And M. A. Khawaja, 1985: Change in street-tree composition of two Urbana, Illinois neighborhoods after fifty years: 1932-1982. *Journal of Arboriculture*, 11, 344-348.

Killus, J.P., Meyer, J.P., Durran, D.R., Anderson, G.E., Jerskey, T.N., Reynolds, S.D. and J. Ames, 1984: Continued research in mesoscale air pollution simulation modeling. Volume 5, Refinements in numerical analysis, transport, chemistry and pollutant removal. EPA/600/3-84/095a, U.S. Environmental Protection Agency, Research Triangle Park, NC.

McPherson, E.G., Minor, C.T. and D.P. Guertin, 1991: A prototype model of residential irrigation water use. Preprints, *Tenth Conference on Biometeorology and Aerobiology and the Special Session on Hydrometeorology*, Salt Lake City, UT, American Meteorological Society, 63-68.

Miller, R. H. And R. W. Miller, 1991: Planting survival of selected street tree taxa. *Journal of Arboriculture*, 17, 185-191.

Nowak, D. J., 1994a: Urban forest structure: the state of Chicago's urban forest. In *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project* (E. G. McPherson, D. J. Nowak, and R. A. Rowntree, eds.), pp. 3-18. General Technical Report No. NE-186, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.

Nowak, D. J., 1994b: Air pollution removal by Chicago's urban forest. In *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project* (E. G. McPherson, D. J. Nowak, and R. A. Rowntree, eds.), pp. 63-82. General Technical Report No. NE-186, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.

NOAA, 1990: Local climatological data, annual summary with comparative data. Sacramento, CA. National Climatic Data Center. Asheville, NC.

Pierce, T. E.; B. K. Lamb and A. R. Van Meter, 1990: Development of a biogenic emissions inventory system for regional scale air pollution models. Proceedings of the 85th Air and Waste Management Association Annual Meeting, Kansas City, Missouri, 90-94.3, 1-16.

Sacramento Metropolitan Air Quality Management District, 1993: BACT cost analysis policy document. SMAQMD, Sacramento, CA.

Sailor, D.J.,1995: Simulated urban climate response to modifications in surface albedo and vegetative cover. *Journal of Applied Meteorology*, 34,1694-1704.

Snyder, R.L., Pruitt, W.O. and D.A. Shaw, undated: Determining daily reference evapotranspiration. Leaflet 21426. Cooperative Extension-University of California, Division of Agriculture and Natural Resources, Oakland, CA.