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

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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 NOx 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 (Corchonoy 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 CO2 emissions from power plants and increased storage of atmospheric CO2 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.

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), 1.5 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 x 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, Duvvuri and Knuuswoja 1983). We assumed that 100 trees were planted, 21 died during the first five years 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 $\mathbf{V}_d$ = 1/($R_\mathbf{C}$+$R_p$+$R_e$), 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 $R_p$, $R_e$, 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 $R_c$. $R_p$ and $R_e$ were estimated for each hour throughout a "base year" (1990) using formulations from the Urban Airshed Model (Kilus et al. 1984, Nowak 1994b).

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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 foliage 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$^2$) (Fierce 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$ ($18,300/ton) (SMAGMD 1993). No cost is listed for ozone because it is formed in the atmosphere and not directly emitted. Because programs to reduce ozone are increasingly aimed at reducing NO$_x$ the control price for NO$_x$ 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

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

where $c_j$ is the annual amount of pollution deposition or emission for pollutant species $j$, $f_{c_j}$ 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 (1915 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 $1.50 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 IUW (m³) was estimated as:

\[
IUW = (ET_o \times P) \times (K \times CP \times \frac{1}{H})
\]

where:

- \(ET_o\) = reference evapotranspiration (m),
- \(P\) = precipitation (m),
- \(K\) = crop coefficient,
- \(CP\) = crown projection (m²),
- \(H\) = 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 m³ ($0.54/100 ft³) 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 m² (5,403 ft²) per tree and averaged 181 m² (1,949 ft²) over the 30 years. When tree mortality is incorporated, the average annual leaf surface area was 129 m² (1,383 ft²) per tree planted.

3.1 Deposition and Emission

Throughout the study period, pollutant removal was greatest for ozone and PM₁₀ (Figure 1). Ozone deposition was nearly five times greater than that for NO₂. SO₂ 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.](image-url)

By year 30, the estimated annual deposition for ozone was 2.73 kg; for PM₁₀ 1.65 kg; for NO₂ 0.55 kg and SO₂ 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\textsubscript{2} in August (0.07 kg) and October (0.12 kg), for SO\textsubscript{2} in April (0.08 kg) and for PM\textsubscript{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 depictions during year 30 occurred in October for ozone (0.29 kg), in May for NO\textsubscript{2} (0.07 kg), in June for PM\textsubscript{10} (0.09 kg), and in September for SO\textsubscript{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

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Amount</th>
<th>fc\textsuperscript{a}</th>
<th>Total</th>
<th>$/yr/tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROC emitted</td>
<td>39.9</td>
<td>88.0</td>
<td>-19.29</td>
<td>(770)</td>
</tr>
<tr>
<td>O\textsubscript{3} uptake</td>
<td>69.8</td>
<td>153.9</td>
<td>27.01</td>
<td>1,885</td>
</tr>
<tr>
<td>NO\textsubscript{2} uptake</td>
<td>14.0</td>
<td>30.9</td>
<td>27.01</td>
<td>378</td>
</tr>
<tr>
<td>PM\textsubscript{10} uptake</td>
<td>39.5</td>
<td>87.1</td>
<td>4.15</td>
<td>462</td>
</tr>
<tr>
<td>SO\textsubscript{2} uptake</td>
<td>2.5</td>
<td>5.5</td>
<td>11.68</td>
<td>50</td>
</tr>
<tr>
<td>Net</td>
<td>85.9</td>
<td>189.4</td>
<td>20.05</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{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 (Sailer, 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 retermine how investments in urban forestry impact air quality, human health, and health care costs.
4.1 Acknowledgments

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4.2 References

Air Resources Board, 1994: California state and local air monitoring network plan. TSP94-001, California Environmental Protection Agency, Sacramento, CA.


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


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.