TREE SPECIES SELECTION, DESIGN, AND MANAGEMENT TO IMPROVE AIR QUALITY

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INTRODUCTION

Urban areas currently occupy 3.5% of the conterminous United States and contain approximately 80% of the U.S. population (Dwyer et al., in press). Many urban areas often have relatively poor air quality that impacts human health. Because of their close proximity to people and numerous emission sources, urban trees affect local and regional air quality. With proper species selection, design, and management, urban trees can help improve air quality.

URBAN TREE EFFECTS ON AIR QUALITY

There are four main ways in which urban trees affect air quality (Nowak, 1995):

- **T**emperature reduction and other microclimatic effects
- **R**emoval of air pollutants
- **E**mission of volatile organic compounds and tree maintenance emissions
- **E**nergy effects on buildings

Temperature Reduction. Tree transpiration and tree canopies affect air temperature, radiation absorption and heat storage, wind speed, relative humidity, turbulence, surface albedo, surface roughness and consequently the evolution of the mixing-layer height. These changes in local meteorology can alter pollution concentrations in urban areas (Nowak et al., 1998). Reduced air temperature due to trees can improve air quality because the emission of many pollutants and/or ozone-forming chemicals are temperature dependent. Decreased air temperature can also reduce ozone formation.

Removal of Air Pollutants. Trees remove gaseous air pollution primarily by uptake via leaf stomata, though some gases are removed by the plant surface. Trees also remove pollution by intercepting airborne particles. The intercepted particle often is resuspended to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall (Smith, 1990). Consequently, vegetation is only a temporary retention site for many atmospheric particles.

In 1994, trees in New York City removed an estimated 1,821 metric tons of air pollution at an estimated value to society of $9.5 million. Air pollution removal by urban forests in New York was greater than in Atlanta (1,196 t; $6.5 million) and Baltimore (499 t; $2.7 million), but pollution removal per m2 of canopy cover was fairly similar among these cities (New York: 13.7 g/m2/yr; Baltimore: 12.2 g/m2/yr; Atlanta: 10.6 g/m2/yr) (Nowak and Crane, in press). These standardized pollution removal rates differ among cities according to the amount of air pollution, length of in-leaf season, precipitation, and other meteorological variables. Large healthy trees greater than 77 cm in diameter remove approximately 70 times more air pollution annually (1.4 kg/yr) than small healthy trees less than 8 cm in diameter (0.02 kg/yr) (Nowak, 1994).

Air quality improvement in New York City due to pollution removal by trees during daytime of the in-leaf season averaged 0.47% for particulate matter, 0.45% for ozone, 0.43% for sulfur dioxide, 0.30% for nitrogen dioxide, and 0.002% for carbon monoxide. In urban areas with 100% tree cover (i.e., contiguous forest stands), short-term improvements in air quality (one hour) from pollution removal by trees were as high as 15% for ozone, 14% for sulfur dioxide, 13% for particulate matter, 8% for nitrogen dioxide, and 0.05% for carbon monoxide (Nowak and Crane, in press).

Emission of Volatile Organic Compounds (VOCs). Emissions of volatile organic compounds by trees can contribute to the formation of ozone and carbon monoxide. However, in atmospheres with low nitrogen oxide concentrations (e.g., some rural environments), VOCs may actually remove ozone (Crutzen et al., 1985; Jacob and Wofsy, 1988). Because VOC emissions are temperature dependent and trees generally lower air temperatures, increased tree cover can lower overall VOC emissions and, consequently, ozone levels in urban areas (Cardelino and Chameides, 1990).

VOC emission rates also vary by species. Nine genera have the highest standardized isoprene emission rate (Geron et al., 1994; Nowak et al., in review), and therefore the greatest relative effect among genera on increasing ozone: beefwood (Casuarina spp.), Eucalyptus spp., sweetgum (Liquidambar spp.), black gum (Nyssa spp.), sycamore (Platanus spp.), poplar (Populus spp.), oak (Quercus spp.), black locust (Robinia spp.), and willow (Salix spp.). However, due to the high degree of uncertainty in atmospheric modeling, results are currently inconclusive as to whether these genera will contribute to an overall net formation of ozone in cities (i.e., ozone formation from VOC emissions is greater than ozone removal).

Because urban trees often receive relatively large inputs of energy, primarily from fossil fuels, the emissions (e.g., carbon dioxide, VOCs, carbon monoxide, nitrogen and sulfur oxides, particulate matter) from equipment used for tree maintenance (e.g., vehicles, chain saws, backhoes) need to be considered in determining the ultimate net effect of urban vegetation on air quality.

Trees in parking lots can also affect evaporative emissions from vehicles, particularly through tree shade. Increasing parking lot tree cover from 8% to 50% could reduce Sacramento County, CA, light duty vehicle VOC evaporative emission rates by 2% and nitrogen oxide start emissions by less than 1% (Scott et al., 1999).

Energy Effects on Buildings. Trees reduce building energy use by lowering temperatures and shading buildings during the summer, and blocking winds in winter (Heisler, 1986). However, they also can 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.

Cumulative Effect of Urban Trees on Ozone. Changes in urban microclimate can affect pollution emission and formation, particularly the formation of ground-level ozone. A model simulation of a 20-percent loss in the Atlanta-area forest due to urbanization led to a 14 percent increase in ozone concentrations for a modeled day (Cardelino and Chameides, 1990). 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 ozone chemistry such that concentrations of ozone 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 with respect to ozone. 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).

Modeling the effects of increased urban tree cover on ozone concentrations from Washington, DC, to central Massachusetts reveals that urban trees generally reduce ozone concentrations in cities. Interactions of the effects of trees on the physical and chemical environment demonstrate that trees can cause changes in pollution removal rates and meteorology, particularly air temperatures, wind fields, and mixing-layer heights, which, in turn, affect ozone concentrations (Nowak et al., 2000).

TREE SPECIES SELECTION TO IMPROVE AIR QUALITY

Tree species selection within urban areas can influence the overall forest effect on air quality. In addition to choosing species that are well-adapted to the site to reduce maintenance needs and increase longevity, tree species characteristics can influence chemical removal, chemical emissions, urban microclimate, and building energy conservation.

Some of the best tree species to improve air quality (Table 1) generally have large leaf surface areas at maturity, leaf characteristics amenable to particle collection (e.g., hairy, sticky), low VOC emissions, and/or relatively high transpiration rates (relatively high air temperature reduction). Although these species may be the best for improving air quality, other species characteristics need to be considered when selecting urban trees (e.g., adaptation to site, maintenance needs, sensitivity to pollution, rooting habit, etc.).

URBAN FOREST DESIGN AND MANAGEMENT TO IMPROVE AIR QUALITY

In addition to species selection, design of the urban forest structure can influence local air quality. Increasing urban tree and shrub cover (both horizontally and vertically) can improve air quality by increasing leaf surface areas through which the polluted air will pass (increased removal), and by deflecting pollutants away from receptors beneath or downwind of the canopy.

Estimates of air-quality improvement due to pollution removal (which can reach up to 15%) likely underestimate the total effect of the forest on reducing ground-level pollutant concentrations because they do not account for the effect of the forest canopy in preventing upper air-pollution concentrations from reaching below-canopy (ground-level) air space. Measured ozone concentration difference between above and below forest canopies in the San Bernardino Mountains of California reached greater than 50 ppb (40% air-quality improvement) (Bytnerowicz et al. 1999). Under normal daytime conditions, atmospheric turbulence mixes the atmosphere such that pollutant concentrations are relatively consistent with height (e.g., Colbeck and Harrison 1985). Forest canopies can limit the mixing of upper air with air below the canopy and lead to significant below-canopy air-quality improvements. However, if there are numerous pollutant sources below the canopy (e.g., automobiles), the forest canopy could have the inverse effect by minimizing the dispersion of the pollutants away from the ground level. Designing vegetation near the source or receptor can have increased effects on improving air quality because pollutant concentrations are higher at the source, which will lead to increased pollutant uptake by the vegetation. Also, vegetation close to the receptor can have local impacts that reduce pollutant concentrations at the ground level near the receptor. Urban forest design and management strategies to help improve air quality include (Nowak, in press):

- Increase the number of healthy trees (increases pollution removal)
- Sustain existing tree cover (maintains pollution removal levels)
- Maximize use of low VOC-emitting trees (reduces ozone and carbon monoxide formation)
- Sustain large, healthy trees (large trees have greatest per tree effects)
- Use long-lived and low-maintenance trees (reduces pollutants emissions from maintenance activities)
- Reduce fossil fuel use in maintaining vegetation (reduces pollutant emissions)
- Plant trees in energy conserving locations (reduces pollutant emissions from power plants)
- Plant trees to shade parked cars (reduces vehicular VOC emissions)
- Supply ample water for vegetation (enhances pollution removal and temperature reduction)
- Plant trees in polluted areas or heavily populated areas (maximizes tree air-quality benefits)
- Avoid pollutant sensitive species (increases tree health)
- Utilize evergreen trees for particulate matter reduction (year-round removal of particles)
- Utilize tree materials for energy production (reduces chemical emissions from power plants)

As urbanization continues to increase on a global scale, proper urban forest design and management will become increasingly important to enhance human health and global environmental quality.

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TABLE 1

Top rated species for improving air quality. List is based on rating the combined effects of pollution removal, VOC emissions, and air temperature reduction of 242 tree species at maturity under average U.S. urban conditions (Nowak et al., in prep). Trees listed are tolerant to pollutant under which it is ranked unless otherwise noted. Overall ranking is based on individual pollutant effects weighted by the average pollutant externality value (estimate of societal cost of pollutant in the atmosphere).

OZONE	CARBON MONOXIDE	OVERALL
Ulmus procera	Tilia americana*	Ulmus procera*
Tilia europea*[I]	Fagus grandifolia	Tilia europea
Fagus grandifolia	Tilia tomentosa*	Liriodendron tulipifera*
Betula alleghaniensis[I]	Ulmus rubra	Metasequoia glyptostroboides*
Liriodendron tulipifera*[S]	Fagus sylvatica	Fagus grandifolia
Tilia americana*	Betula alleghaniensis	Tilia platyphyllos*
Fagus sylvatica	Tilia euchlora*	Betula alleghaniensis
Tilia platyphyllos*[S]	Ulmus procera*	Fagus sylvatica
Metasequoia glyptostroboides*	Ginkgo biloba*	Tilia americana*
Betula papyrifera	Liriodendron tulipifera*	Ulmus americana
		Ulmus thomas

PARTICULATE MATTER	SULFUR / NITROGEN DIOXIDE	OVERALL
		Chamaecyparis lawsoniana
Ulmus procera*	Ulmus procera*[I/U]	Tsuga heterophylla
Platanus occidentalis*	Tilia europea*[T/S]	Tilia cordata*
Chamaecyparis lawsoniana	Populus deltoides[T]	Tsuga mertensiana
Cupressocyparis x leylandii	Platanus occidentalis*[T]	Tilia tomentosa*
Juglans nigra	Platanus x acerifolia*[T]	Betula papyrifera
Eucalyptus globulus	Metasequoia glyptostroboides*[T]	Celtis laevigata*
Tilia europea	Liriodendron tulipifera*[T]	Fraxinus excelsior*
Abies alba	Juglans nigra[S/U]	Ulmus crassifolia
Larix decidua	Betula alleghaniensis[S]	Betula nigra*
Picea rubens	Fagus grandifolia	Larix decidua

* Species or various cultivars of species rated as recommended trees for street use or urban conditions (Bassuk et al., 1998; Bridwell, 1994; Flint, 1997). Note: hardiness zone and other tree factors need to be considered in urban tree selection.

I intermediate tolerance to pollutant

S sensitive to pollutant

T tolerant to sulfur dioxide (SO_2); unknown tolerance to nitrogen dioxide (NO_2).

I/U Intermediate tolerance to SO_2; unknown tolerance to NO_2

S/U Sensitive to SO_2; unknown tolerance to NO_2

T/S Tolerant to SO_2; sensitive to NO_2

the tree, run under the paving, and are interconnected from tree to tree or to a remote rooting area.

TREE BASE PROTECTION:

The area around the base of the tree should be designed to permit constant enlargement of the trunk flare. The use of metal tree grates to cover and protect this soil is discouraged. Tree grates may damage the tree base if not frequently enlarged. They also collect trash and can be a tripping hazard. The resources spent on tree grates would be better spent on more soil.

Bark mulch is the best material to protect the soil at the base of the tree. Low maintenance, short, coarse ground cover plants are also effective. Low metal fences to mark the edge of the bed, help keep pedestrians away from the tree and increase the range of places where groundcover plantings may be effective. Flexible sand set paving materials such as gravel, stone dust or loose laid stone or brick pavers are a reasonable alternative to metal tree grates in places where ground cover may not be acceptable. No pavers should be placed within 300mm of the base of the trunk to allow plenty of space for growth.

CONCLUSION:

Fundamentally, urban trees simply need more earth in which to grow. Finding space at the surface of the ground in urban areas is often difficult. Using a new approach to urban tree planting is not so much about learning a specific new standard techniques as it is about understanding the scientific basis for tree survival and designing solutions that meet the needs of the unique site conditions where the tree is to be planted.

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