UFORE Methods

The UFORE model uses standard field, air pollution, and meteorological data to quantify urban forest structure and numerous forest-related effects in various U.S. cities (Nowak and Crane 2000). Currently, there are five model components:

UFORE-A: Anatomy of the Urban Forest -- quantifies urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass) based on field data.

UFORE-B: Biogenic Volatile Organic Compound (VOC) Emissions -- quantifies: 1) hourly urban forest VOC emissions (isoprene, monoterpenes, and other VOC emissions that contribute to O_3 formation) based on field and meteorological data, and 2) O_3 and CO formation based on VOC emissions.

UFORE-C: Carbon Storage and Sequestration -- calculates total stored C, and gross and net C sequestered annually by the urban forest based on field data.

UFORE-D: Dry Deposition of Air Pollution -- quantifies the hourly amount of pollution removed by the urban forest and associated percent improvement in air quality throughout a year. Pollution removal is calculated for O_3, SO_2, NO_2, CO, and PM10 based on field, pollution concentration, and meteorological data.

UFORE-E: Energy Conservation – estimates effects of trees on building energy use and consequent emissions of carbon from power plants.

The following text details the general methods of a UFORE analysis. For specific data (e.g., number of plots sampled), the reader should refer to the metadata table found on the bottom of the results web page for the specific analysis (http://www.fs.fed.us/ne/syracuse/Data/data.htm). Other analysis specific information may also be found within the result tables. The methods detailed below are for a full UFORE analysis (see http://www.fs.fed.us/ne/syracuse/Tools/downloads/UFORE_Manual.pdf for more specific field data collection details and instructions), however some of the data collection groups may have elected not to collect all of the data.

UFORE-A: Urban Forest Structure

Urban forest structure is the spatial arrangement and characteristics of vegetation in relation to other objects, e.g., buildings, within urban areas (e.g., Nowak 1994a). During the in-leaf season 0.04 ha field plots (see metadata table for number of plots sampled) were either: a) randomly distributed (a-priori) among the land-use types in proportion to the estimated amount of tree cover, or b) randomly distributed within equal area grid cells such that the number of grid cells equals the total number of plot desired. With the randomized grid approach, the plots are stratified by land use type post-priori. For information on number of plots in each land use strata, see table 21 (Species Diversity Indices by Land Use).

On each plot, the following general plot data were estimated/recorded:

- Percent tree cover
- Actual land use on the plot

- Percent of plot within the land use
- Ground cover: percent of ground covered by following cover types: buildings, cement, tar-blacktop/asphalt, other impervious, soil, pervious rock, duff/mulch, herbaceous (exclusive of grass and shrubs), maintained grass, wild/unmaintained grass, and water.
- Percent shrub cover

For each shrub mass, the following information was recorded: genus, height, percent of shrub mass volume devoid of leaves, and percent of total shrub area in the plot occupied by the shrub mass.

For each tree with the center of its stem in the plot, minimum diameter at breast height (d.b.h.) of 2.54 cm, the following information was measured/recorded:
- species
- number of stems
- d.b.h. of each stem (or if greater than six stems, diameter recorded below fork and height of measure recorded)
- tree height
- height to base of live crown
- crown width (average of two perpendicular measurements).
- percent of branch dieback in crown (used to rate tree crown condition):
    - E (< 1)
    - G (1-10)
    - F (11-25)
    - P (26-50)
    - C (51-75)
    - D (76-99)
    - K (100 -- no leaves)
- Percent of canopy volume devoid of leaves (0-100%)
- Percent of land area beneath entire tree canopy's drip line that is impervious
- Percent of land area beneath canopy drip line that is occupied by shrubs
- Crown Light Exposure: Number of sides of the tree receiving sunlight from above
- Distance to residential building (if with 60 feet of tree)
- Direction to building
- Street tree: Y if a street tree, N if not.

Leaf area and leaf biomass

Leaf area and leaf biomass of individual trees were calculated using regression equations for deciduous urban species (Nowak 1996). If shading coefficients (percent light intensity intercepted by foliated tree crowns) used in the regression did not exist for an individual species, genus or hardwood averages were used. For deciduous trees that were too large to be used directly in the regression equation, average leaf-area index (LAI: m^2 leaf area per m^2 projected ground area of canopy) was calculated by the regression equation for the maximum tree size based on the appropriate height-width ratio and shading coefficient class of the tree. This LAI was applied to the ground area (m^2) occupied by the tree to calculate leaf area (m^2). For deciduous trees with height-to-width ratios that were too large or too small to be used directly in the regression equations, tree height or width was scaled downward to allow the crown to the reach maximum (2) or minimum (0.5) height-to-width ratio. Leaf area was calculated using the regression equation with the maximum or minimum ratio; leaf area was then scaled back proportionally to reach the original crown volume.

For conifer trees (excluding pines), average LAI per height-to-width ratio class for deciduous trees with a shading coefficient of 0.91 were applied to the tree's ground area to calculate leaf area. The 0.91 shading coefficient class is believed to be the best class to represent conifers as conifer forests typically have about 1.5 times more LAI than deciduous forests (Barbour et al. 1980), the average shading coefficient for deciduous trees is 0.83 (Nowak 1996); 1.5 times the 0.83 class LAI is equivalent to the 0.91 class LAI. Because pines have lower LAI than other conifers and LAI that are comparable to hardwoods (e.g., Jarvis and Leverenz 1983; Leverenz and Hinckley 1990), the average shading coefficient (0.83) was used to estimate pine leaf area.

Tree leaf biomass could not be calculated directly from regression equations (due to tree parameters being out of equation range), so leaf biomass was calculated by converting leaf-area estimates using species-specific measurements of g leaf dry weight/m^2 of leaf area.[1] Shrub leaf biomass was calculated as the product of the crown volume occupied by leaves (m^3) and measured leaf biomass factors ($g\ m^{-3}$) for individual species (e.g., Winer et al. 1983; Nowak 1991). Shrub leaf area was calculated by converting leaf biomass to leaf area based on measured species conversion ratios ($m^2\ g^{-1}$).[1] Due to limitations in estimating shrub leaf area by the crown-volume approach, shrub leaf area was not allowed to exceed a LAI of 18. If there are no leaf-biomass-to-area or leaf-biomass-to-crown-volume conversion factors for an individual species, genus or hardwood/conifer averages were used.[1]

Average tree condition was calculated by assigning each condition class a numeric condition rating. A condition rating of 1 indicates no dieback (excellent); a condition rating of 0 indicates a dead tree (100-percent dieback). Each code between excellent and dead was given a rating between 1 and 0 based on the mid-value of the class (e.g., fair = 11-25 percent dieback was given a rating of 0.82 or 82-percent healthy crown. Estimates of leaf area and leaf biomass were adjusted downward based on crown leaf dieback (tree condition).

To adjust for overlapping tree crowns, estimates of tree leaf area and leaf biomass (derived from open-grown tree equations) were scaled back proportional to the amount of crown competition
on the plot. A plot competition factor (CF) was calculated as:

$$CF = GA / TA \quad (1)$$

where GA = projected crown area (m^2) of individual trees in the plot and TA = % tree cover × plot size (m^2). Leaf area (LA_n) of individual trees was calculated as:

$$LA_n = LA_0 \times LAI_n / LAI_0 \quad (2)$$

where LA_0 = leaf area based on open-grown equations; LAI_0 = LAI of plot based on open-grown equations; and LAI_n = LAI adjusted for plot competition. LAI_n varied with CF. For CF $\leq$ 1 (open-grown trees): $LAI_n = LAI_0$. For CF > 1 and CF < 2 (mixed open-grown and closed-canopy conditions):

$$LAI_n = LAI_{op} + LAI_{cl} \quad (3)$$

where:

$$LAI_{op} = LAI_0 \times (1 - ((GA - TA) / TA)) \quad (4)$$

[1]Nowak, D.J.; Klinger, L.; Karlik, J.; Winer, A; Harley, P. and Abdollahi, K. Tree leaf area -- leaf biomass conversion factors. Unpublished data on file at Northeastern Research Station, Syracuse, NY.

$$LAI_{cl} = [\ln((1-\bar{x}_s)^{CF})/-k] \times (GA-TA)/TA \quad (5)$$

where $\bar{x}_s$ is average shading coefficient in the plot; LAI_{op} is leaf area for open-grown trees; LAI_{cl} is leaf area in closed canopies, which is based on estimating LAI from light intensity using the Beer-Lambert Law:

$$LAI = \ln(I/I_O)/-k \quad (6)$$

where I = light intensity beneath canopy; I_o = light intensity above canopy; and k = light extinction coefficient (Smith et al. 1991). The plot light extinction coefficient was:

$$k = (\%CON \times 0.52) + (\%HRD \times 0.65) \quad (7)$$

where %CON is the percent of plot crown area occupied by conifers and %HRD is the percent of plot crown area occupied by hardwoods. The light extinction coefficients for conifers (0.52) and hardwoods (0.65) were from Jarvis and Leverenz (1983).

For CF $\geq$ 2 (closed canopies):

$$LAI_n = \ln((1-\bar{x}_s)^{CF})/-k \quad (8)$$

If crown light exposure (CLE) values were collected, formulas 1-8 were not used, rather leaf area was adjusted on a per tree basis. For trees with CLE = 4-5: leaf area was based on open-grown equations; CLE = 0-1: leaf area was based on LAI of closed canopy x canopy area:

$$LA = [\ln((1-x_s)/-k\ ] \times \pi r^2 \quad (9)$$

Where x_s is shading coefficient of tree; k = 0.52 for conifers and 0.65 for hardwoods; and r = crown radius. For CLE = 2-3: leaf area was calculated as the average of leaf area from the open-grown and closed canopy equations.

Species Diversity

Species diversity indices (Shannon-Wiener's index) and species richness, i.e., number of species (Barbour et al. 1980), were calculated for living trees for the entire city. The proportion of the tree population that originated from different parts of the country and world was calculated based on the native range of each species (e.g., Hough 1907; Grimm 1962; Platt 1968; Little 1971, 1976, 1977, 1978; Viereck and Little 1975; Preston 1976; Clark 1979; Burns and Honkala 1990a,b; Gleason and Cronquist 1991).

Compensatory Value

The structural or compensatory value of the trees was based on methods from the Council of Tree and Landscape Appraisers (1992). Compensatory value, which is based on the replacement cost of a similar tree, is used for monetary settlement for damage or death of plants through litigation, insurance claims of direct payment, and loss of property value for income tax deduction. Other values can be ascribed to trees based on such factors as increases in local property values or environmental functions provided (e.g., air pollution reduction), but compensatory valuation is the most direct method.

Compensatory value is based on four tree/site characteristics: trunk area (cross-sectional area at dbh), species, condition, and location. Trunk area and species are used to determine the basic value, which is then multiplied by condition and location ratings (0-1) to determine the final tree compensatory value.

For transplantable trees, average replacement cost and transplantable size were obtained from International Society of Arboriculture (ISA) publications (ACRT 1997) to determine the basic replacement price (dollars/cm^2 of cross-sectional area) for the tree. The basic replacement price from the state (or nearest state if no state data are available) was multiplied by trunk area and species factor (0-1) to determine a tree's basic value. The minimum basic value for a tree prior to species adjustment was set at $150. Local species factors also were obtained from ISA publications. If no species data were available for the state, data from the nearest state were used.

For trees larger than transplantable size the basic value (BV) was:

$$BV = RC + (BP \times [TA_A - TA_R] \times SF) \tag{10}$$

where RC (replacement cost) is the cost of a tree at the largest transplantable size, BP (basic price) is the local average cost per unit trunk area (dollars/cm^2), TA_A is trunk area of the tree being appraised, TA_R is trunk area of the largest transplantable tree and SF is the local species factor.

For trees larger than 76.2 cm in trunk diameter, trunk area was adjusted downward based on the premise that a large mature tree would not increase in value as rapidly as its truck area. The following adjusted trunk-area formula was determined based on the perceived increase in tree size, expected longevity, anticipated maintenance, and structural safety (Council of Tree and Landscape Appraisers 1992):

$$ATA = -0.335d^2 + 176d - 7020 \tag{11}$$

where ATA = adjusted trunk area and d = trunk diameter in inches.

Basic value was multiplied by condition and location factors (0-1) to determine the tree's compensatory value. Condition factors were based on percent crown dieback: excellent (< 1) = 1.0; good (1-10) = 0.95; fair (11-25) = 0.82; poor (26-50) = 0.62; critical (51-75) = 0.37; dying (76-99) = 0.13; dead (100) = 0.0.

Available data required using location factors based on land use type (Int. Soc. of Arboric. 1988): golf course = 0.8; commercial/industrial, cemetery and institutional = 0.75; parks and residential = 0.6; transportation and forest = 0.5; agriculture = 0.4; vacant = 0.2; wetland = 0.1.

As an example of compensatory value calculations, if a tree that is 40.6 cm in diameter (1,295 cm^2 trunk area) has a species rating of 0.5, a condition rating of 0.82, a location rating of 0.4, a basic price of $7 per cm^2, and a replacement cost of $1,300 for a 12.7-cm-diameter tree (127 cm^2 trunk area), the compensatory value would equal:

$$[1{,}300 + (7 \times (1{,}295 - 127) \cdot 0.5)] \times 0.82 \times 0.4 = \$1{,}767$$

Data for individual trees were used to determine the total compensatory value of trees.

Insect Effects

The proportion of leaf area and live tree population, and estimated compensatory value in various susceptibility classes to gypsy moth feeding (Liebhold et al. 1995; Onstad et al. 1997); Asian longhorned beetle (e.g.,Nowak et al., 2001); and emerald ash borer (all ash species) were calculated to reveal potential urban forest damage associated with these pests.

Land Use

Land use determined in the field was cross-referenced with land use classified by the land-use map to determine the map's accuracy. Data in this report are given by land-use classes as defined by the map. However, what is identified as one use on the map may contain samples from other use types. Possible reasons for this discrepancy are map error or changes in land use in the field since the map was produced.

The proportion of species population, leaf area, and leaf biomass in each d.b.h. class are calculated, as are the proportion of species population by condition class and by d.b.h. and condition class. Field data were input into the UFORE-A module to calculate totals, averages, and standard errors by species, land use, and city totals for urban forest structure. The standard errors for leaf area and leaf biomass report sampling error rather than error of estimation. The reported sampling errors underestimate the actual standard errors. Lack of information regarding errors in the allometric equations and adjustment factors make it impossible to fully account for estimation errors.

UFORE-B: Biogenic Emissions

Volatile organic compounds (VOCs) can contribute to the formation of O_3 and CO (e.g., Brasseur and Chatfield 1991). The amount of VOC emissions depends on tree species, leaf biomass, air temperature, and other environmental factors. UFORE-B estimates the hourly emission of isoprene (C_5H_8), monoterpenes (C_{10} terpenoids), and other volatile organic compounds (OVOC) by species for each land use and for the entire city. Species leaf biomass (from UFORE-A) is multiplied by genus-specific emission factors (Nowak et al, 2002a) to produce emission levels standardized to 30^{o}C and photosynthetically active radiation (PAR) flux of 1,000 µmol m^{-2} s^{-1}. If genus-specific information is not available, median emission values for the family, order, or superorder are used. Standardized emissions are converted to actual emissions based on light and temperature correction factors (Geron et al. 1994) and local meteorological data.

VOC emission (E) (in µgC tree^{-1} hr^{-1} at temperature T (K) and PAR flux L (µmol m^{-2} s^{-1})) for isoprene, monoterpenes, and OVOC is estimated as:

$$E = B_E \times B \times \gamma \tag{12}$$

where B_E is the base genus emission rate (Appendix B) in µgC (g leaf dry weight)$^{-1}$ hr^{-1} at 30^{o}C and PAR flux of 1,000 µmol m^{-2} s^{-1}; B is species leaf dry weight biomass (g) (from UFORE-A); and:

$$\gamma = [\alpha \cdot c_{L1} L / (1 + \alpha^2 \cdot L^2)^{\frac{1}{2}}] \cdot [\exp[c_{T1}(T - T_S) / R \cdot T_S \cdot T] / (0.961 + \exp[c_{T2}(T - T_M) / R \cdot T_S \cdot T])] \tag{13}$$

for isoprene where L is PAR flux; α = 0.0027; c_{L1} = 1.066; R is the ideal gas constant (8.314 K^{-1} mol^{-1}), T(K) is leaf temperature, which is assumed to be air temperature, T_S is standard temperature (303 K), and T_M = 314K, C_{T1} = 95,000 J mol^{-1}, and C_{T2} = 230,000 J mol^{-1} (Geron et al. 1994; Guenther et al. 1995; Guenther 1997). As PAR strongly controls the isoprene emission rate, PAR is estimated at 30 canopy levels as a function of above-canopy PAR using the sunfleck canopy environment model (A. Guenther, Nat. Cent. for Atmos. Res., pers. commun., 1998) with the LAI from UFORE-A.

For monoterpenes and OVOC:

$$\gamma = \exp[\beta(T - T_S)] \tag{14}$$

where T_S = 303 K, and β = 0.09.

Hourly inputs of air temperature are from measured National Climatic Data Center (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).

Because tree transpiration cools air and leaf temperatures and thus reduces biogenic VOC emissions, tree and shrub VOC emissions were reduced based on model results of the effect of increased urban tree cover on O_3 in the Northeastern United States (Nowak et al. 2000). For the modeling scenario analyzed (July 13-15, 1995), increased tree cover reduced air temperatures by 0.3° to 1.0°C, resulting in hourly reductions in biogenic VOC emissions of 3.3 to 11.4 percent. These hourly reductions in VOC emissions were applied to the tree and shrub emissions during the in-leaf season to account for tree effects on air temperature and its consequent impact on VOC emissions.

To estimate the amount of O_3 produced by the VOC emissions, the O_3 incremental reactivity scales (g O_3 produced/g VOC emitted) for isoprene, monoterpenes, and OVOC were used (Carter 1994, 1998). The incremental reactivity values used were based on scaling estimates of existing values to represent the VOC/NO_x conditions in the city. VOC/NO_x conditions were based on data from the Natural Resource Council (1991). If city VOC/NO_x conditions were not listed, the closest city data were applied.

There is a relatively high degree of uncertainty in applying the incremental reactivity rates, particularly in winter. However, vegetation has relatively low emission rates during this period, so the effect of trees on O_3 formation is minimal. As O_3 is formed during daylight hours, incremental reactivity values were multiplied by daytime VOC emissions to calculate overall O_3 formation due to tree VOC emissions.

As CO formation can contribute to O_3 formation, CO formation due to tree emissions also were subsequently converted to O_3 formation (Table 1). Zimmerman et al. (1978) found that 60 percent of VOC emissions have been converted to CO, though recent evidence suggests that this conversion potential is closer to 10 percent (S. Madronovich, Nat. Cent. for Atmos. Res., pers. commun., 1997). UFORE-B uses an average VOC to CO conversion factor of 10 percent. Estimates of CO formation are calculated as:

$$COFP = 0.1 \times E \times R \quad (15)$$

where COFP is CO formation potential (g), *E* is the VOC emission (gC), and *R* is the atomic weight ratio of CO/C (2.33). CO emissions were then converted to O_3 formation based on incremental reactivity scales.

Incremental reactivity scales and CO formation estimates are a reasonable yet simplified approach to estimate the multiple, complex chemical reactions that form O_3 and CO. They are used in the model to give a rough approximation of the amount of pollution formed due to biogenic VOC emissions and atmospheric conditions in the city. However, due to the high degree of uncertainty in the approaches of estimating VOC emissions and consequently pollution formation, no estimates of the amount of pollution formed by various species are given. Rather, estimates of the net effect of trees on O_3 (pollution formation minus pollution removal) are used to create a relative species index of trees species effects on these pollutants. Although the estimation of pollution formation has a high degree of uncertainty, all species use the same approach; thus, index values can be used to compare the relative impact of the species on O_3.

The individual species/genera O_3 index values range from 100, which represents species with the lowest possible pollution formation potential (i.e., no emission of isoprene or monoterpene), to zero, which is represented by a species (e.g., *Liquidambar* sp.) with the highest pollution formation potential (highest standardized total VOC emissions).

A total urban-forest, air-quality species index score was created by weighting the individual species/genera index values by the amount of leaf biomass in the species/genera. A total score of 100 represents a forest composition where all species have the maximum effect on reducing O_3 (lowest possible VOC emissions and O_3 formation); a score of zero represents a composition with minimum effect on reducing O_3 (highest possible VOC emissions and O_3 formation). If the management objective is to reduce O_3, higher index scores will reduce VOC emissions and consequent O_3 formation. However, high scores (i.e., 100) may not be feasible in many urban forests as species diversity may be minimized.

UFORE-C: Carbon Storage and Annual Sequestration

Increasing levels of atmospheric CO_2 and other greenhouse gases (e.g., methane, chlorofluorocarbons, nitrous oxide) are thought to contribute to an increase in atmospheric temperatures by the trapping of certain wavelengths of radiation in the atmosphere (U.S. Nat. Res. Council, 1983). Through growth processes, trees remove atmospheric CO_2 and store C within their biomass.

Biomass for each measured tree was calculated using allometric equations from the literature (see Nowak 1994b; Nowak et al., 2002b). Equations that predict above-ground biomass were converted to whole tree biomass based on root-to-shoot ratio of 0.26 (Cairns et al., 1997). Equations that compute fresh-weight biomass were multiplied by species- or genus- specific-conversion factors to yield dry-weight biomass. These conversion factors, derived from average moisture contents of species given in the literature, averaged 0.48 for conifers and 0.56 for hardwoods (USDA 1955; Young and Carpenter 1967; King and Schnell 1972; Wartluft 1977; Stanek and State 1978; Wartluft 1978; Monteith 1979; Clark et al. 1980; Ker 1980; Phillips 1981; Husch et al. 1982; Schlaegel 1984a,b,c,d; Smith 1985).

Open-grown, maintained trees tend to have less above-ground biomass than predicted by forest-derived biomass equations for trees of the same diameter at breast height (Nowak, 1994b). To adjust for this difference, biomass results for urban trees were multiplied by a factor 0.8 (Nowak, 1994b). No adjustment was made for trees found in more natural stand conditions (e.g., on vacant lands or in forest preserves). As deciduous trees drop their leaves annually, only carbon stored in wood biomass was calculated for these trees. Total tree dry-weight biomass was converted to total stored carbon by multiplying by 0.5 (Forest Products Lab, 1952; Chow and Rolfe 1989).

The multiple equations used for individual species were combined together to produce one predictive equation for a wide range of diameters for individual species. The process of combining the individual formulas (with limited diameter ranges) into one, more general species formula, produced results that were typically within 2% of the original estimates for total carbon storage of the urban forest (i.e., the estimates using the multiple equations). Formulas were combined to prevent disjointed sequestration estimates that can occur when calculations switch between individual biomass equations.

If no allometric equation could be found for an individual species, the average of results from equations of the same genus was used. If no genus equations were found, the average of results from all broadleaf or conifer equations was used.

To estimate monetary value associated with urban tree carbon storage and sequestration, carbon values were multiplied by $20.3/tC based on the estimated marginal social costs of carbon dioxide emissions (Fankhauser, 1994).

Urban Tree Growth and Carbon Sequestration

Average diameter growth from the appropriate land-use and diameter class was added to the existing tree diameter (year *x*) to estimate tree diameter in year *x+1*. For trees in forest stands, average d.b.h. growth was estimated as 0.38 cm/yr (Smith and Shifley 1984); for trees on land uses with a park-like structure (e.g., parks, cemeteries, golf courses), average d.b.h. growth was 0.61 cm/yr (deVries 1987); for more open-grown trees, d.b.h. class specific growth rates were based on Nowak (1994b). Average height growth was calculated based on formulas from Fleming (1988) and the specific d.b.h. growth factor used for the tree.

As the base growth estimates used are from more northern U.S. areas, the growth and carbon sequestration rates are likely to be conservative in more southern regions. This growth approach was used in UFORE versions less than 1.0 (SAS code). For the newer UFORE C++ code (Versions >= 1.0), a new growth approach was used that utilizes length of growing season to determine the base growth rate.

To determine a base growth rate based on length of growing season, urban street tree (Frelich, 1992; Fleming, 1988; and Nowak, 1994b), park tree (DeVries, 1987), and forest growth estimates (Smith and Shifley, 1984) were standardized to growth rates for Minnesota (153 frost free days) based on:
Standardized growth = measured growth x (153/ number of frost free days of measurement) (16)

Average standardized growth rates for street (open-grown) trees was 0.83 cm/yr. Growth rates of trees of the same species or genera were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Park growth averaged 1.78 times less than street trees; and forest growth averaged 2.29 times less than street tree growth. Crown light exposure (CLE) measurements of 0-1 were used to represent forest growth conditions; 2-3: park conditions; and 4-5: open-grown conditions. Thus, the growing season adjusted growth equations (UFORE version >=1.0) are:

Standardized growth (SG) = 0.83 cm/yr x number of frost free days / 153 (17)

and for: CLE 4-5: Base growth = SG (18)

CLE 2-3: Growth = SG / 1.78

CLE 0-1: Growth = SG / 2.26

Growth rates were adjusted based on tree condition. For trees in fair to excellent condition, base growth rates were multiplied by 1 (no adjustment), poor trees' growth rates were multiplied by 0.76, critical trees by 0.42, and dying trees by 0.15 (dead trees' growth rates = 0). Adjustment factors were based on percent crown dieback and the assumption that less than 25-percent crown dieback had a limited effect on d.b.h. growth rates. The difference in estimates of C storage between year *x* and year *x+1* is the gross amount of C sequestered annually.

Tree death leads to the eventual release of stored C. In estimating the net amount of C sequestered by the urban forest, C emissions due to decomposition after tree death must be considered. To calculate the potential release of carbon due to tree death, estimates of annual mortality rates by condition class were derived from a study of street-tree mortality (Nowak 1986). Annual mortality was estimated as 1.92 percent for trees 0 to 3 inches in the good-excellent class; 1.46 percent for trees more than 3 inches in the good-excellent class; 3.32 percent for trees in fair condition; 8.86 percent for poor condition; 13.08 percent for critical condition; 50 percent dying trees, and 100 percent for dead trees.

Two types of decomposition rates were used: 1) rapid release for above-ground biomass of trees that are projected to be removed, and 2) delayed release for standing dead trees and tree roots of removed trees. Trees that are removed from urban areas are not normally developed into wood products for long-term carbon storage (i.e., removed trees are often burned or mulched), therefore they will most likely release their carbon relatively soon after removal.

If dead trees are not removed annually, they have an increased probability of being measured in the tree sample and decomposition rates must reflect this difference. All trees on vacant and transportation land uses, and 50% of trees in parks, were assumed to be left standing (i.e., not removed) as these trees are likely within forest stands and/or away from intensively maintained sites. These trees were assumed to decompose over a period of 20 years[2]. Trees on all other land uses were assumed to be removed within one year of tree death. For removed trees, above-ground biomass was mulched with a decomposition rate of three years[3]; below-ground biomass was assumed to decompose in 20 years.

Estimates of C emissions due to decomposition were based on the probability of the tree dying within the next year and the probability of the tree being removed using the formula:

$$Emission = C \times M_c \times \sum p_i((D_{remove}) + (D_{stand})) \quad (19)$$

$$D_{remove} = (p_{ab} / y_i)(1/d_m) + ((1 - p_{ab})/y_i)(1/d_r) \quad (20)$$

$$D_{stand} = ((y_i - 1)/y_i)(1/d_r) \quad (21)$$

where Emission = individual tree contribution to carbon emissions; C = carbon storage in the next year; M_c = probability of mortality based on condition class; i = decomposition class (based on number of years left standing before removal); p_i = proportion of the land use tree population in decomposition class i; p_{ab} = proportion of tree biomass above ground; y_i = number of years left standing before removal ($y_i \rightarrow \infty$ for dead trees that will never be cut down (natural decomposition)); d_m = decomposition rates for mulched above-ground biomass (3 years); and d_r = decomposition rate for standing trees and tree roots (20 years).

Individual tree estimates of mortality probability and decomposition rates were aggregated upward to yield total estimates of decomposition for the tree population. The amount of carbon sequestered due to tree growth was reduced by the amount lost due to tree mortality to estimate the net carbon sequestration rate.

UFORE-D: Air Pollution Removal

UFORE-D was used to estimate dry deposition of air pollution (i.e., pollution removal during nonprecipitation periods) to trees and shrubs (Nowak et al. 1998). This module calculates the hourly dry deposition of O_3, SO_2, NO_2, and CO, and PM10 to tree canopies throughout the year based on tree-cover data, hourly NCDC weather data, and U.S. Environmental Protection Agency (EPA) pollution-concentration monitoring data. See metadata table year of weather and pollution data used.

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[2]There are few data on tree decomposition rates. Using decomposition rates of 10 to 50 years had little effect on the overall net decomposition.

[3]Although no mulch decomposition studies could be found, studies on decomposition reveal that 37-56% of carbon in tree roots and 48-67% of carbon in twigs is released within the first three years (Scheu and Schauermann, 1994).

In UFORE-D, the pollutant flux (F; in g m^{-2} s^{-1}) is calculated as the product of the deposition velocity (V_d; in m s^{-1}) and the pollutant concentration (C; in g m^{-3}):

$$F = V_d \times C \tag{22}$$

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):

$$V_d = (R_a + R_b + R_c)^{-1} \tag{23}$$

Hourly meteorological data from the closest weather station (usually airport weather stations) were used in estimating R_a and R_b. See metadata table for location of weather station used. The aerodynamic resistance is calculated as (Killus et al. 1984):

$$R_a = u(z) \times u_*^{-2} \tag{24}$$

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

$$u_* = (k \times u(z-d))[\ln((z-d) \times z_o^{-1}) - \psi_M((z-d) \times L^{-1}) + \psi_M(z_o \times L^{-1})]^{-1} \tag{25}$$

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):

$$\psi_M = 2\ln[0.5(1+X)] + \ln[0.5(1+X^2)] - 2\tan^{-1}(X) + 0.5\pi \tag{26}$$

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

$$u_* = C_{DN} \times u\{0.5 + 0.5[1 - (2u_o / C_{DN}^{\frac{1}{2}} \times u))^2]^{\frac{1}{2}}\} \tag{27}$$

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

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

$$R_b = 2(Sc)^{\frac{2}{3}}(\mathrm{Pr})^{-\frac{2}{3}}(k \times u_*)^{-1} \tag{28}$$

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

In-leaf, hourly tree canopy resistances for O_3, SO_2, and NO_2 were calculated based on a modified hybrid of big-leaf and multilayer 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:

$$1/R_c = 1/(r_s + r_m) + 1/r_t \tag{29}$$

Mesophyll resistance was set to zero s m^{-1} for SO_2 (Wesely 1989) and 10 s m^{-1} for O_3 (Hosker and Lindberg 1982). Mesophyll resistance was set to 100 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^o), windspeed (m s^{-1}), u_* (m s^{-1}), CO_2 concentration (set to 360 ppm), and absolute humidity (kg m^{-3}). Air temperature, windspeed, u_*, and absolute humidity are measured directly or calculated from measured hourly NCDC meteorological data. Total solar radiation is calculated based on the METSTAT model 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 CO and removal of particulate matter by vegetation are 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 median deposition velocity from the literature (Lovett 1994) was 0.0128 m s^{-1} for the in-leaf season. Base particle V_d was set to 0.064 based on a LAI of 6 and a 50-percent resuspension rate of particles back to the atmosphere (Zinke 1967). The base V_d was adjusted according to actual LAI and in-leaf vs. leaf-off season parameters.

The model uses tree and shrub LAI and percent tree and shrub leaf area that are evergreen from UFORE-A calculations. 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; 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 monitors in or near the city. If no local monitor data could be found, data from nearby cities of similar size were used. See metadata table for number and location of monitors used. 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. Missing hourly meteorological or pollution-concentration data are estimated using the monthly average for the specific hour. In several locations, an entire month of pollution-concentration data may be missing and are estimated based on interpolations from existing data. For example, O_3 concentrations may not be measured during winter months and existing O_3 concentration data are extrapolated to missing months based on the average national O_3 concentration monthly pattern.

Average hourly pollutant flux (g m^{-2} of tree canopy coverage) among the pollutant monitor sites was multiplied by total 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).

The monetary value of pollution removal by trees is estimated using the median externality values for the United States for each pollutant. These values, in dollars per metric ton (t) are: NO_2 = \$6,752 t^{-1}, PM10 = \$4,508 t^{-1}, SO_2 = \$1,653 t^{-1}, and CO = \$959 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 the nearest location with similar geography were used (see metadata table for location). Daily morning and afternoon mixing heights were interpolated to produce hourly values using the EPA's PCRAMMIT program (US 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, which is common in daytime (unstable conditions) (e.g., Colbeck and Harrison 1985). The amount of pollution in the air was contrasted with the amount removed by trees on an hourly basis to calculate the relative effect of trees in reducing local pollution concentrations:

$$E = R(R + A)^{-1} \qquad (30)$$

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

The ability of individual trees to remove pollutants was estimated for each diameter class using the formula (Nowak 1994c):

$$I_x = R_t \times (LA_x / LA_t) / N_x \qquad (31)$$

where I_x = pollution removal by individual trees in diameter class *x* (kg/tree); R_t = total pollution removed for all diameter classes (kg); LA_x = total leaf area in diameter class *x* (m^2); LA_t = total leaf area of all diameter classes (m^2); and N_x = number of trees in diameter class *x*. This formula yields an estimate of pollution removal by individual trees based on leaf surface area (the major surface for pollutant removal).

UFORE-E: Building Energy Effects

UFORE-E estimates the effects of trees on building energy use and consequent emissions of carbon from power plants. Methods for these estimates are based on a report by McPherson and Simpson (1999). For each tree within 18 m of two-story or less residential buildings, information on distance and direction to the building was recorded. Any energy tree that was smaller than 6 meters in height or farther than 18 meters from a building was considered to have no effect on building energy use.

Using the tree size, distance, direction to building, climate region, leaf type (deciduous or evergreen) and percent cover of buildings and trees on the plot, the amount of carbon avoided from power plants due to the presence of trees was calculated based on methods in McPherson and Simpson (1999). The amount of carbon avoided was categorized into the amount of MWh (cooling), and MBtus and MWh (heating) avoided due to tree energy effects. Default energy effects per tree were set for each climate region, vintage building types (period of construction), tree size class, distance from building, energy use (heating or cooling) and/or leaf type (deciduous or evergreen) depending upon the energy effect of the tree (tree shade, windbreak effects, and local climate effect) (McPherson and Simpson, 1999). Default shading and climate effect values were applied to all trees; heating windbreak energy effects were assigned to each evergreen tree. As shading effect default values were on given for one vintage building type (post-1980), vintage adjustment factors (McPherson and Simpson, 1999) were applied to obtain shading effect values for all other vintage types.

Tree Condition Adjustment

To adjust for varying energy effects of trees due to tree condition, the default energy effect values (McPherson and Simpson, 1999) were adjusted for the tree condition as follows:

$$\text{Energy adjustment} = 0.5 + (0.5 \text{ x tree condition}) \qquad (28)$$

where tree condition = 1 - % dieback.

This adjustment factor was applied to all tree energy effects for cooling, but only evergreen trees for the heating energy use effects.

Local Climate Effects

As tree cover increases in an area, the individual tree effect on climate diminishes, though the total effect of all trees can increase. Base climate effect values for a tree were given for plots of 10, 30 and 60 % cover (McPherson and Simpson, 1999). Interpolation formulas (McPherson and Simpson, 1999) were used to determine the actual tree value based on the specific plot percent tree and building cover. For plots with less than 10% cover, the slope between the 10 and 30 % cover values was used for the interpolation. Plots with percent cover greater than 60 % used the slope between 30 and 60 % cover with a minimum individual tree climate effect of one-third the effect at 60% cover. This minimum was set to prevent a tree from obtaining a zero or negative effect at high cover (100%).

The total shading, windbreak, and climate energy effects due to trees on a plot were calculated by summing the individual tree's energy effects for the particular energy use and housing vintage. These values were adjusted for the distribution of the different vintage types within the climate region (McPherson and Simpson, 1999).

Since the default cooling energy effects were determined based on the climate regions' electricity emissions factors, it was necessary to convert the cooling energy effects to the state specific equivalent. This conversion was accomplished by multiplying all of the plot cooling energy effects by the ratio of the state specific electricity emissions factor to the climate region's electricity emissions factor (McPherson & Simpson, 1999).

Home heating source distribution (e.g., fuel oil, heat pump, electricity, natural gas) for the region was used to partition the carbon emissions from heating to the appropriate energy source. Standard conversion factors (t CO_2 / MWh, t CO_2 / MBtu) were used to convert the energy effect from t CO_2 to units of energy saved (MBtus, MWh). Cooling and heating electricity use (MWh) had state specific conversion factors; non-electrical heating fuels (MBtus) used a standard conversion factor because this factor does not vary by region (McPherson and Simpson, 1999). Total plot effects were combined to yield the total energy and associated carbon effect due to the urban forest.

To determine the estimated economic impact of the change in building energy use, state average price per kWh between 1970 and 2002 (Energy Information Administration, 2003a) and per MBtu for natural gas, residential fuel, and wood between 1990 and 2002 (Energy Information Administration, 2003b-f) were used. All prices were adjusted to 2002 dollars using the consumer price index (U.S. Department of Labor and Statistics, 2003). State prices were used to determine the value of energy effects. Average price for heating change due to trees was based on the average distribution of buildings in the region that heat by natural gas, fuel oil, and other (including wood) (McPherson and Simpson, 1999).

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