Northeastern Research Station

Urban Forests, Human Health, and Environmental Quality   *Syracuse, NY*

Project Summary

Urban Canopy Enhancements through Interactive Mapping

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Introduction

Through funding by the USDA Forest Service State and Private Forestry, numerous groups (New York Public Interest Research Group's Community Mapping Assistance Project, Trees New York, Council on the Environment, ESRI, and the U.S. Forest Service) have collaborated to develop and test a system by which field data can be collected, mapped, and accessed by the public through the Open Accessible Spaces Information System (OASIS). Three study areas were chosen for analysis: South Bronx, South Manhattan, and North Staten Island. As part of this project, the USDA Forest Service in Syracuse had the following objectives:

1. Develop high-resolution cover maps of the three neighborhoods
2. Analyze street tree data collected in the neighborhoods (e.g., carbon storage, air pollution removal, tree values)
3. Provide tree analysis data in format that can be linked into OASIS GIS maps
4. Develop maps and map layers that can be used to select best locations to plant trees and calculate tree benefits/values

Study Areas

The three study areas for this project were:

- South Bronx
- South Manhattan
- North Staten Island

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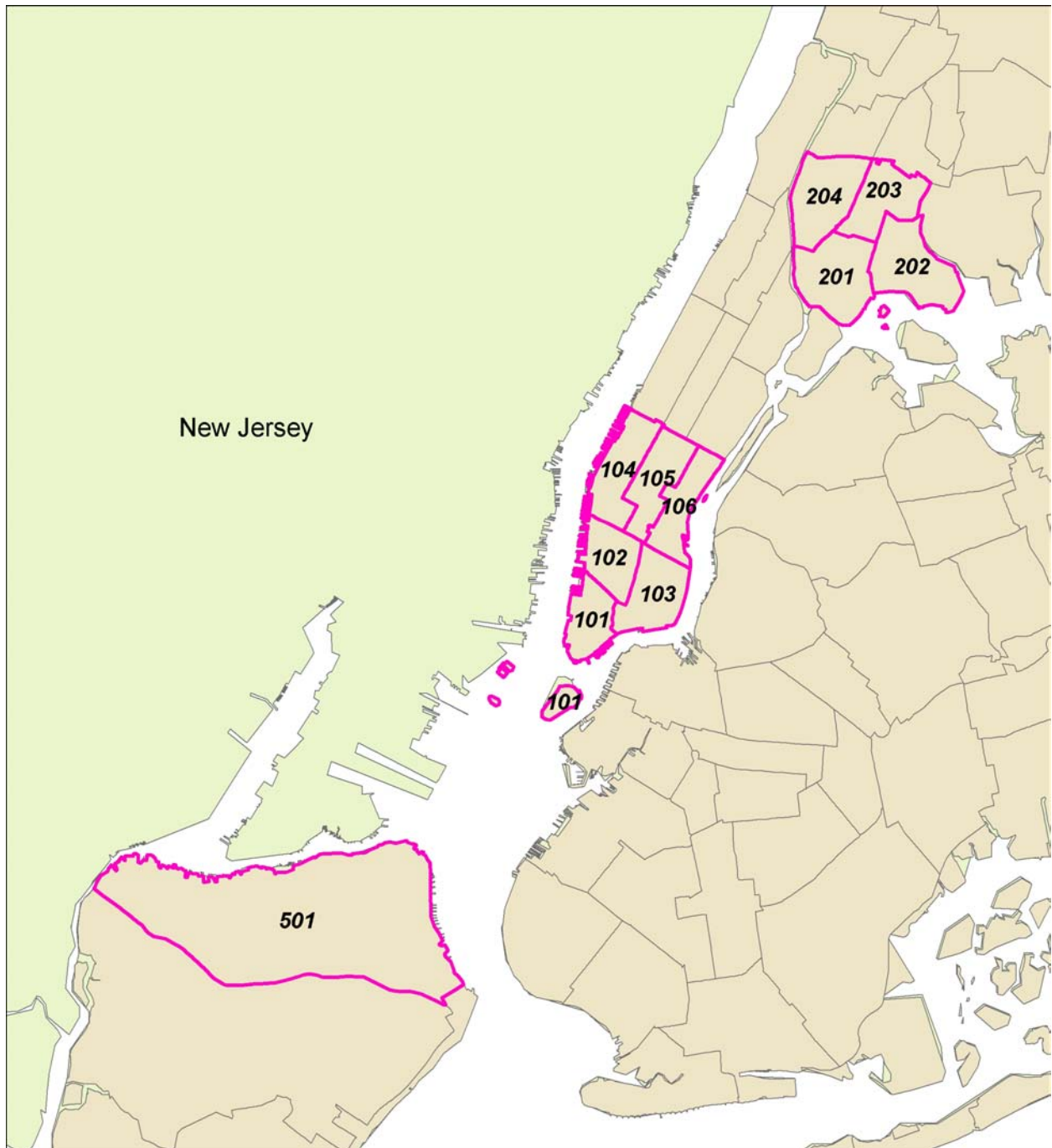
Figure 1. Study areas in New York City with corresponding Community Area numbers. South Bronx has community areas 201-204; South Manhattan has areas 101-106; and North Staten Island is area 501.

High Resolution Cover Maps

Using color infrared images (3-foot resolution) collected in September, 2001 by Emerge Corporation, a digital cover map of the three neighborhoods was developed. This cover map classifies each pixel as either tree/shrub, grass/soil, impervious (building or other) or water.

The cover map was developed based on unsupervised classification of the 3 bands of Emerge data (green, red, near infrared) and texture bands using Erdas Imagine ® software. Tree cover was highest in Staten Island (29%), followed by the South Bronx (15.3%) and Lower Manhattan (11.1%). Cover types in each neighborhood were classified as:

Neighborhood	Tree	Grass	Impervious ground	Building	Shadow	Water
South Bronx – 201	11.5	7.9	55.4	24.4	0.0	0.8
South Bronx – 202	8.9	8.0	56.7	25.2	0.0	1.2
South Bronx – 203	24.7	7.2	46.8	20.6	0.5	0.2
South Bronx – 204	18.9	4.2	49.9	25.4	1.1	0.6
Manhattan – 101	12.8	4.3	38.4	31.8	5.0	7.6
Manhattan – 102	9.3	0.1	38.9	46.4	2.8	2.5
Manhattan – 103	21.4	1.1	44.3	30.3	2.6	0.3
Manhattan – 104	6.9	0.1	42.4	43.1	4.7	2.7
Manhattan – 105	2.8	0.0	34.5	54.7	7.9	0.0
Manhattan – 106	12.6	0.6	41.1	39.6	5.0	1.1
Staten Island – 501	29.0	13.7	35.1	14.4	3.7	4.2

Figure 2. Example of Emerge image for the South Bronx

Figure 3. Example of cover map for South Bronx (dark green is trees; light green is grass; gray is buildings; tan is impervious ground cover, blue is water).

As these maps are based on analyzing reflectance values, some errors do occur due to similar reflectance patterns of various objects. The following is a summary of the user's accuracy for the three neighborhoods. The accuracy of the maps was assessed by comparing photo interpretation of randomly located points against the cover type predicted by the cover map. A total of 200 points were analyzed in the Bronx; 603 points in Manhattan; and 589 points in Staten Island. Overall, the classification accuracy in the Bronx was 96%; 80% in Manhattan; and 74% in Staten Island.

User's Accuracy for South Bronx, South Manhattan, and North Staten Island

Category	South Bronx	South Manhattan	North Staten Island
tree	71.4	76.6	73.6
grass	88.2	80.0	47.3
impervious	100	83.4	80.4
shadow	na	11.7	47.4
water	98.0	93.3	96.0
Overall	95.6	80.1	73.5

Street Tree Data

Street tree data were input into the Urban Forest Effects (UFORE) model to analyze individual tree carbon storage, annual carbon sequestration and carbon value; air pollution removal and value; and tree compensatory value based on the Council of Tree and Landscape Appraisers (see references). Results for individual trees were mapped to their specific location on a map using GIS.

The inventory data were collected by Citizen Pruners for 50 trees in the Bronx, 60 trees in Manhattan, and 212 trees in Staten Island.

The following collected data were input into the UFORE model for analysis and reporting:
- street address
- species (Appendix 1.1).
- number of stems .
- diameter at breast height (4.5 feet)
- tree height.
- height to base of live crown.
- crown width (average of two perpendicular measurements).
- tree condition (based on percent of branch dieback in crown):
  - Excellent (< 1)
  - Good (1-10)
  - Fair (11-25)
  - Poor (26-50)
  - Critical (51-75)
  - Dying (76-99)
  - Dead (100 -- no leaves)
- Percent of canopy volume occupied by leaves (0-100%)

The UFORE model output the following results for each tree (detailed methods are given the Appendix):
- Ground area (m2) – the area of the tree canopy projected to the ground.
- Leaf area (m2) – the amount of leaf area (one-side) in the tree.
- Leaf area index – leaf area divided by ground area.

- Leaf biomass (kg) – the dry weight of the leaf biomass.
- Carbon storage (kg) – amount of carbon currently stored within the tree (this carbon has been accumulated over the life of the tree).
- Carbon storage value ($) – value of the carbon storage based on the estimated marginal social costs of carbon dioxide emissions of $20.3 tC.
- Gross carbon sequestration (kg / yr) – estimated amount of carbon to be accumulated over the next year due to tree growth.
- Gross carbon sequestration value ($ / yr) - value of the carbon sequestration based on the estimated marginal social costs of carbon dioxide emissions of $20.3 tC.
- Structural tree value ($) – value of tree based on a combination of Council of Tree and Landscape Appraisers (CTLA) formulas.
- Native or Exotic – Is the tree native to New York State (Yes or No).
- Pollution removal (g / yr) – amount of carbon monoxide, nitrogen dioxide, ozone, particulate matter less than 10 microns, and sulfur dioxide removed by the tree based on 2000 pollution and weather conditions.
- Pollution removal value ($ / yr) – value of pollution removal based on median externality values for United States for each pollutant.
- Volatile organic compound emissions (g / yr) – annual emissions of isoprene, monoterpene and other volati9le organic compounds based on 2000 weather conditions.

Results of the analysis reveal that the 322 inventoried street trees:
- Store approximately 203 metric tons of carbon ($4,100 value)
- Remove about 4.3 metric tons of carbon annually ($90 value)
- Have a structural or compensatory value of around $1 million
- Remove about 228 kg of pollution per year ($1,250 annual value)
  - 99 kg of ozone ($670 annual value)
  - 51 kg of nitrogen dioxide ($345)
  - 38 kg of particulate matter less than 10 microns ($170)
  - 28 kg of sulfur dioxide ($45)
  - 12 kg of carbon monoxide ($12)
- Emit approximately 80 kg of volatile organic compounds annually
  - 52 kg of isoprene
  - 9 kg of monoterpenes
  - 20 kg of other volatile organic compounds

Individual tree results can be found in the following files:

- Tree inventory data – Bronx.xls
- Tree inventory data – Manhattan.xls
- Tree inventory data – Staten Island.xls
- Tree inventory data – Summary.xls

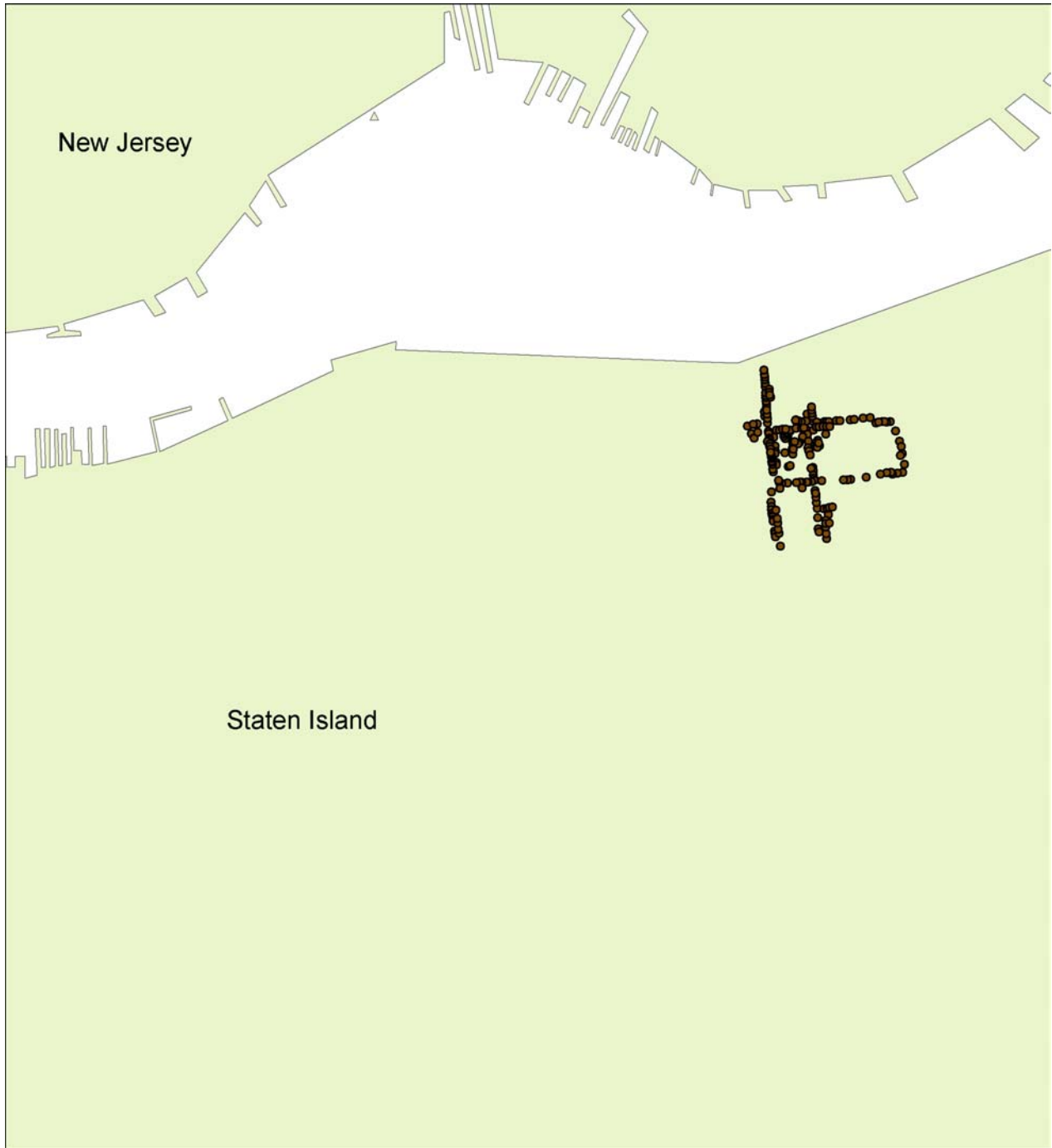**Figure 4.** Street tree locations in the three study areas.

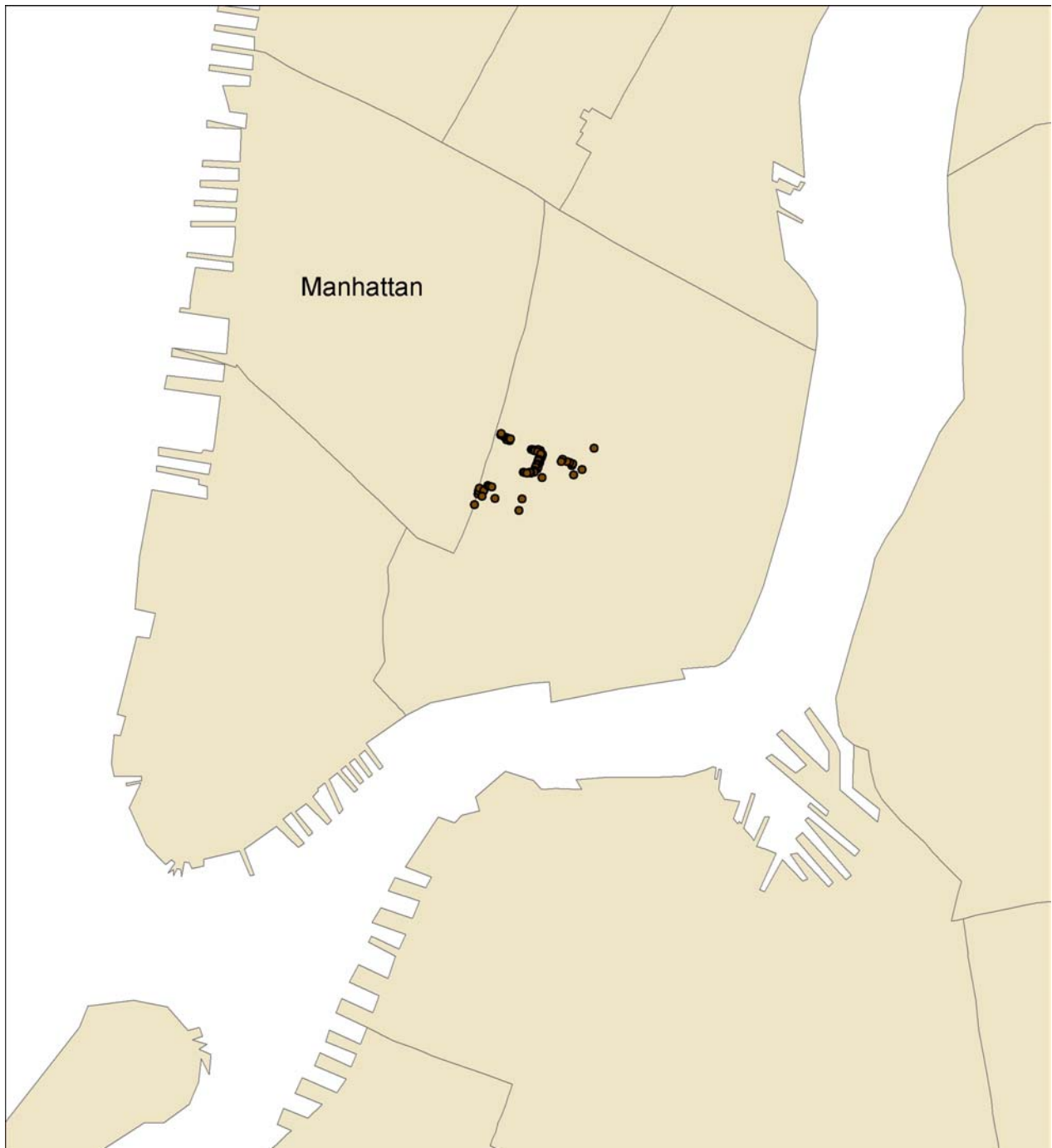**Figure 5.** Street tree locations in Staten Island (212 trees).

Figure 6. Street tree location in Manhattan (60 trees)

Figure 7. Street tree locations in the Bronx (50 trees).

Determining Planting Locations

To determine the best locations to plant trees, data from the cover map were used in conjunction with 2000 U.S. Census data to produce an index of planting priority. Index values were produced for each census block with the higher the index value, the higher the priority of the area for tree planting. The criteria used to make the index were:

- Population density: the greater the population density, the greater the priority for tree planting
- Tree stocking levels: the lower the tree stocking level (the percent of available greenspace (tree, grass, and soil cover areas) that is occupied by tree canopies), the greater the priority for tree planting
- Tree cover per capita: the lower the amount of tree canopy cover per capita (m^2/capita), the greater the priority for tree planting

Each criteria was standardized[4] on a scale of 0 to 1 with 1 representing the census block with the highest value in relation to priority of tree planting (i.e., the census block with highest population density, lowest stocking density or lowest tree cover per capita were standardized to a rating of 1). Individual scores were combined based on the following formula to produce an overall priority index value between 0 and 100:

$$I = (PD * 40) + (TS * 30) + (TPC * 30)$$

Where I = index value, PD is standardized population density, TS is standardized tree stocking, and TPC is standardized tree cover per capita. Based on this index, Planting priority maps were produced.

GIS Data

Individual tree estimates and maps for incorporation into the OASIS GIS database have been burned onto a CD and sent to Steve Romalewski and Matt Arnn. These CDs include GIS layers of:

- Emerge color infrared images
- Cover maps
- Individual street tree benefits for inventoried trees
- Pollution removal and value per unit of tree cover
- Planting priority index

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[4] Standardized value for population density was calculated as $V = (n - m) / r$, where V is the value (0-1), n is the value for the census block (population / km^2), m is the minimum value for all census blocks, and r is the range of values among all census blocks (maximum value – minimum value). Standardized value for tree stocking was calculated as $V = (100 - ((T/(T+G)) * 100)) / 100$, where V is the value (0-1), T is percent tree cover, and G is percent grass cover. Standardized value for tree cover per capita was calculated as $V = 1 - [(n - m) / r]$, where V is the value (0-1), n is the value for the census block (m^2/capita), m is the minimum value for all census blocks, and r is the range of values among all census blocks (maximum value – minimum value).
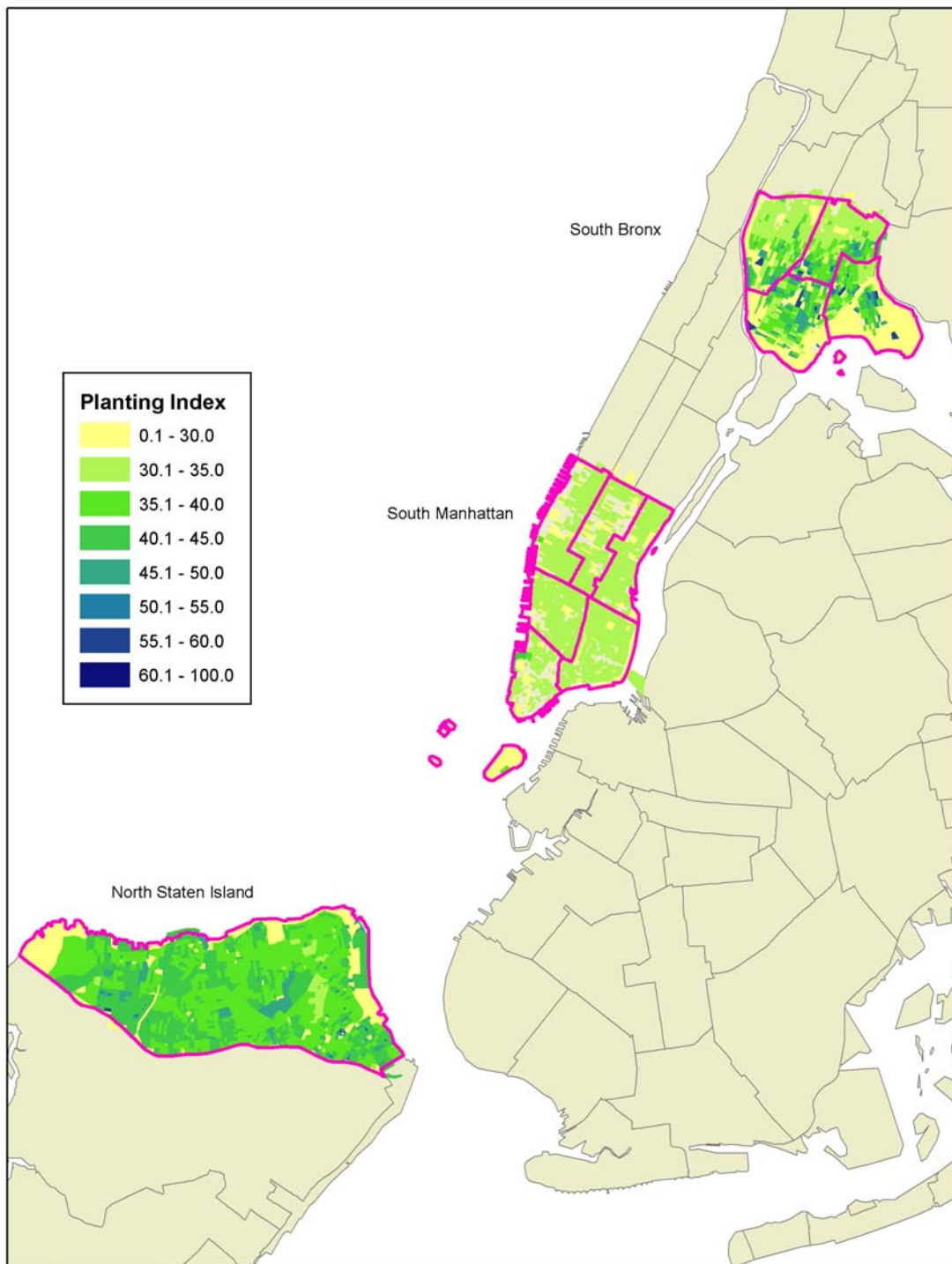
Best Locations to Plant Trees:

Figure 8. Priority planting index for three study areas (100 = highest priority)
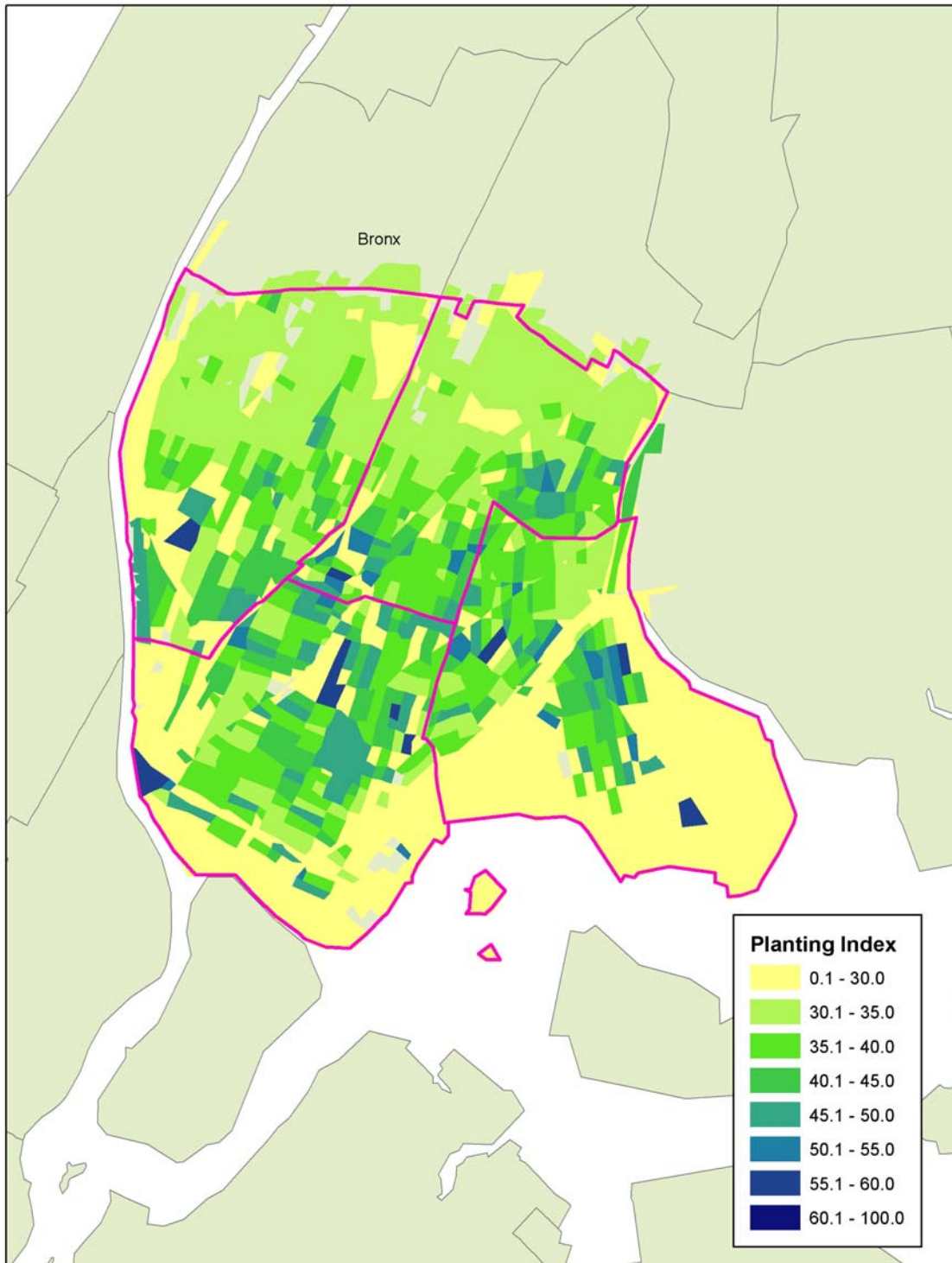
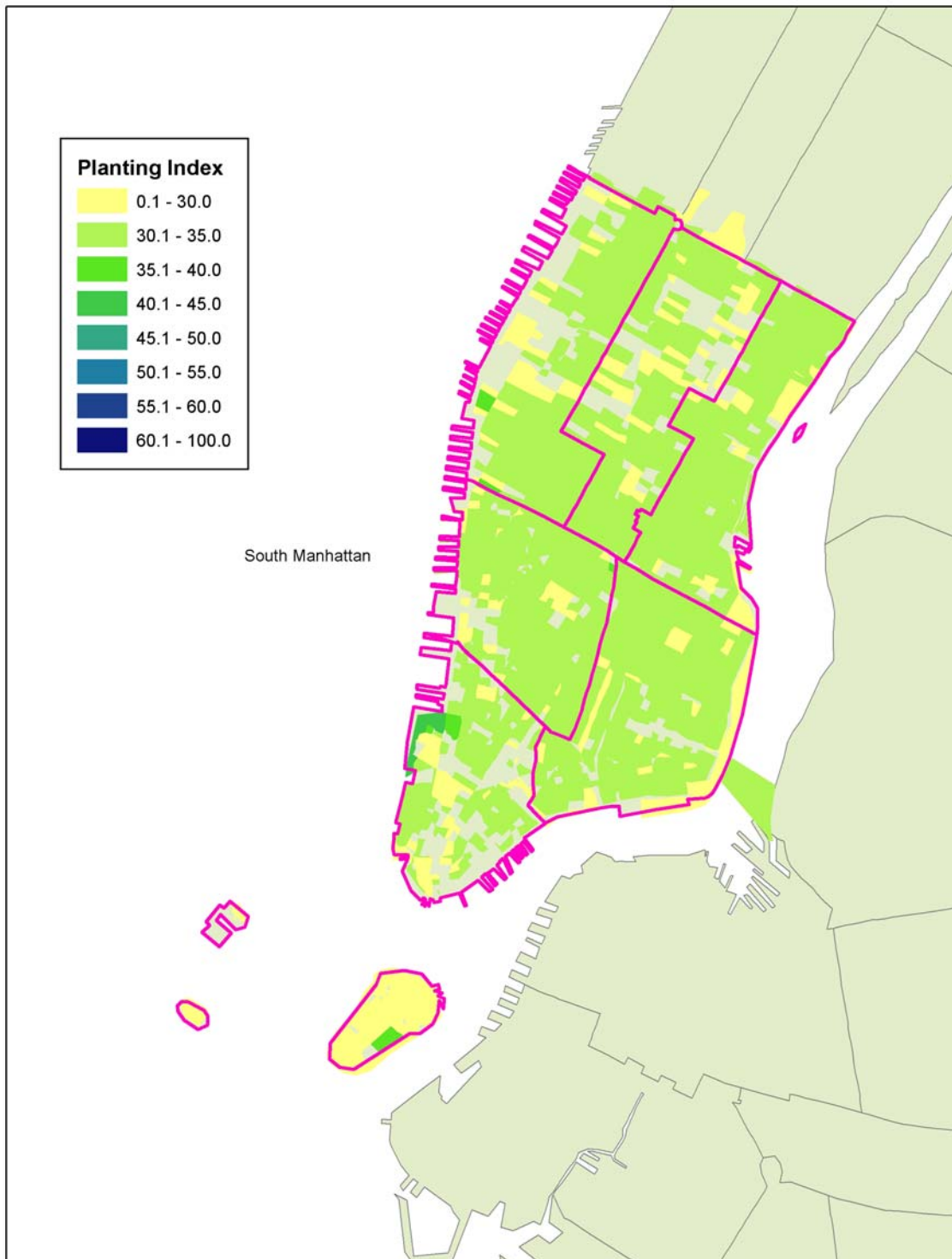**Figure 9.** Priority planting index for South Bronx (100 = highest priority)

Figure 10. Priority planting index for South Manhattan (100 = highest priority)
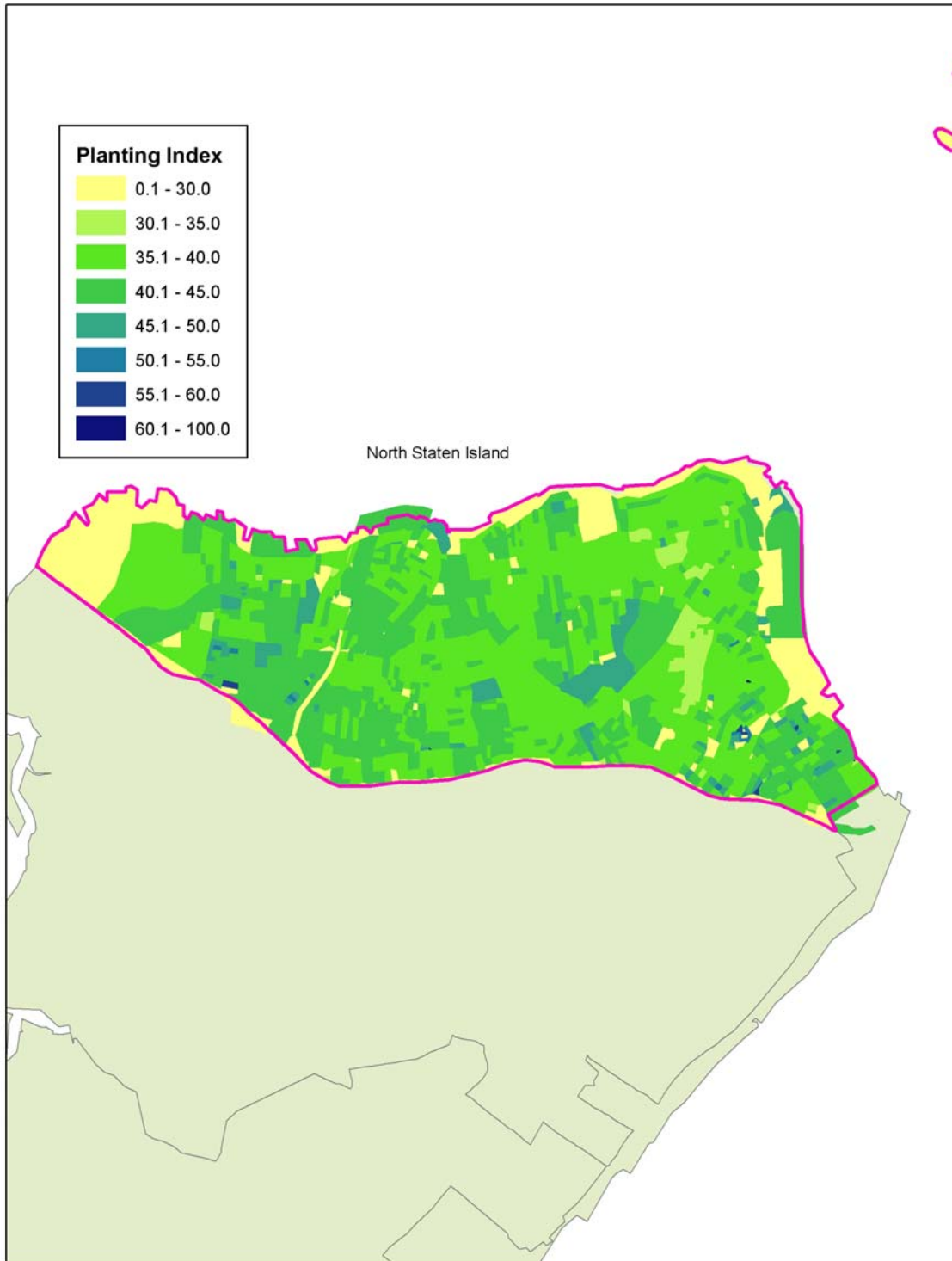
Figure 11. Priority planting index for North Staten Island (100 = highest priority)

Air Pollution Removal

To estimate pollution removal in each area, tree cover data were combined with: a) 2000 hourly pollution concentration data from EPA air quality monitors and b) 2000 hourly weather data from LaGuardia airport within the Urban Forest Effects (UFORE) model (see References). Local monitor data from each area were used in calculating the pollution removal estimates. For South Bronx, the monitoring locations were: E. 156 St. between Dawson and Kelly for nitrogen dioxide (NO_2), ozone (O_3), particulate matter less than 10 microns (PM10), and sulfur dioxide (SO_2). As no local monitor of carbon monoxide (CO) existed, the city-wide average was used. For Manhattan, the monitoring locations were: Mabel Dean High School for SO_2, NO_2, O_3, and PM10, and the Post Office at 350 Canal St. for CO. For Staten Island, the monitoring locations were: Susan Wagner High School for SO_2, O_3, and PM10, and the city-wide average for NO_2 and CO.

Standardized pollution removal values (g pollution removed / m^2 of canopy cover) varied among the neighborhoods:

Pollutant	South Bronx	South Manhattan	N. Staten Island
Ozone	2.47	2.50	4.33
Particulate matter less than 10 μm	1.45	2.21	1.84
Nitrogen dioxide	1.57	2.71	2.38
Sulfur dioxide	1.12	0.68	0.31
Carbon monoxide	0.45	0.53	0.45
Total	7.05	8.65	9.30

The values differ among the area based on pollution concentration values. The standardized values along with standardized pollution removal values ($/$m^2$ of canopy cover) were applied to the tree cover map to calculate out pollution removal and map pollution removal per capita differences among census blocks.

Based on the UFORE analyses, a total of 143 metric tons of pollution in 2000 ($814,000 dollar annual value) is estimated to be removed by trees annually in the three areas:

Pollutant	Pollutant Removal (metric tons)		
	South Bronx	South Manhattan	N. Staten Island
Ozone	7.8	6.7	45.6
Particulate matter less than 10 μm	4.6	5.9	19.4
Nitrogen dioxide	4.9	7.3	25.1
Sulfur dioxide	3.5	1.8	3.2
Carbon monoxide	1.4	1.4	4.7
Total	22.2	23.2	98.0

Figure 12. Pollution removal per capita in the three study areas

Total Pollutant Removal per Capita

South Bronx

| | Community Boards |

Total Pollutants (g/person)

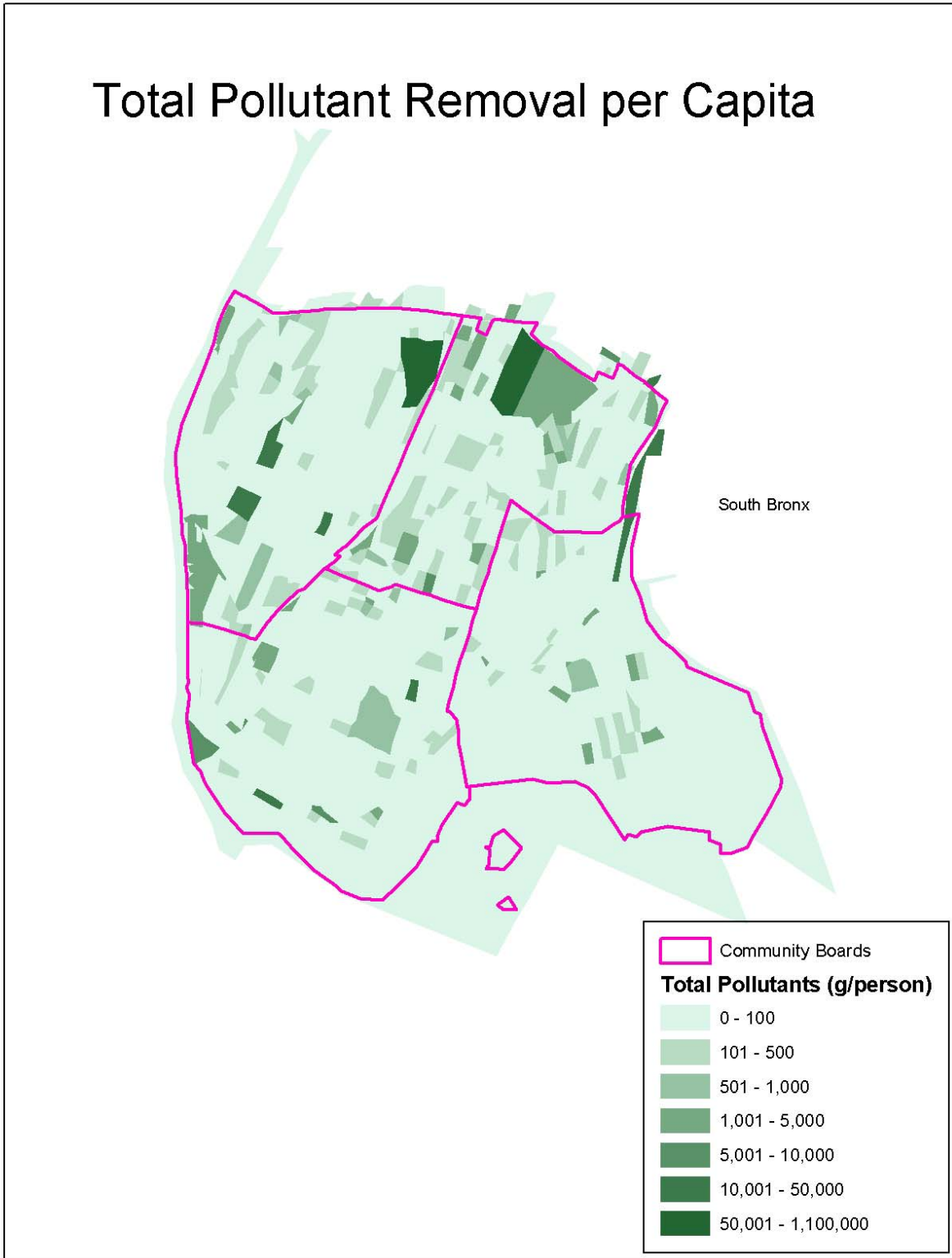| | 0 - 100 |
	101 - 500
	501 - 1,000
	1,001 - 5,000
	5,001 - 10,000
	10,001 - 50,000
	50,001 - 1,100,000

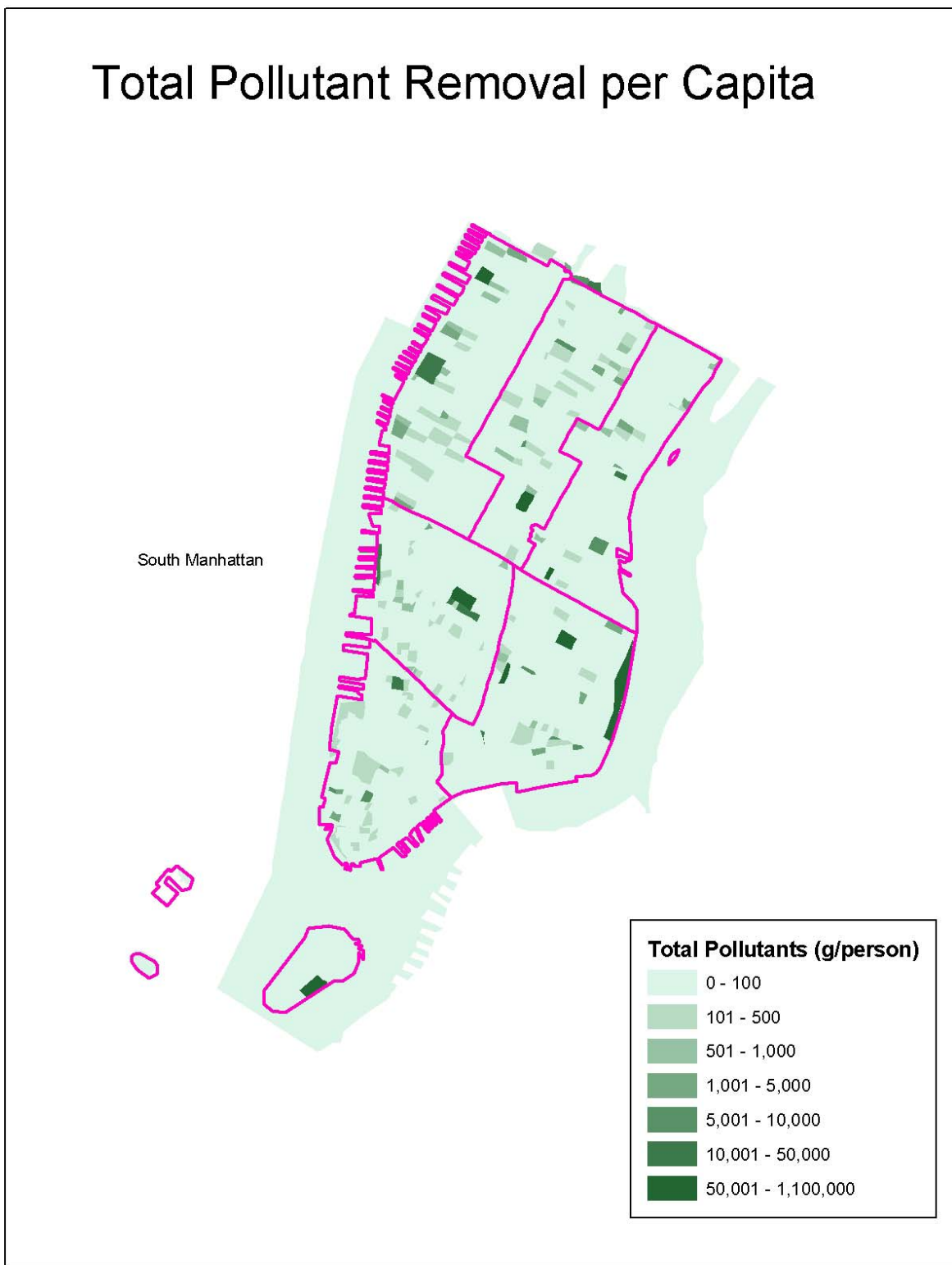**Figure 13**. Pollution removal per capita in the South Bronx

Figure 14. Pollution removal per capita in the South Manhattan
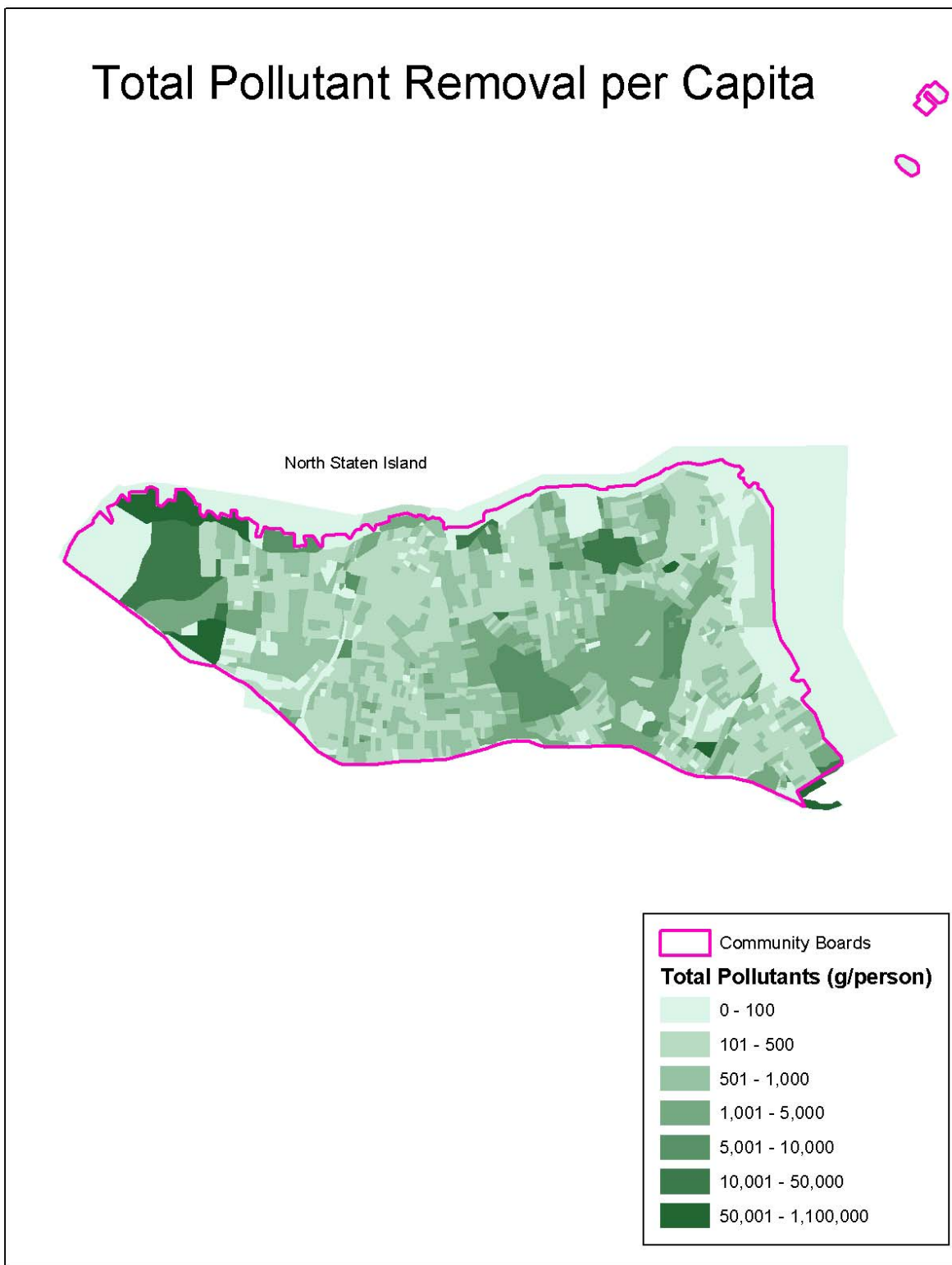
Figure 15. Pollution removal per capita in the North Staten Island

Implications for Management

The data presented in this report can have significant implications for urban forest management. These data will be incorporated in the OASIS web site to provide access to these data to help make improved management decisions. There are four new data layers that can be used to improve management. The first is the new cover map for the three areas. This digital map allows vegetation and its spatial location to be incorporated within local management decisions. New maps based on 2002 Emerge data are currently being completed, such that the entire New York City area plus some surrounding regions will have digital cover maps similar to the maps developed for this project. Incorporating vegetation as layer in local and regional planning and management is important for sustaining vegetation health and its associated environmental benefits.

To help quantify some of these benefits, GIS layers of pollution removal and value are available for estimating pollution removal effects of vegetation in at neighborhood or block scale, projecting the future effects of sustaining the existing canopy, and projecting the impact of projects designed to increase tree cover. In addition to the cover map pollution data, individual tree effects on air pollution and carbon dioxide (the dominant greenhouse gas related to global warming) have been calculated for street trees measured in each of the three areas. The tree and functional data and values are available in GIS format so that better management decisions can be made for these specific street trees.

The last new project data available for OASIS are maps detailing the census blocks within the study areas that have the highest priority of planting based on tree cover and population data. These maps reveal the areas where tree planting efforts could be given priority to sustain a more equitable distribution of tree cover. Decisions on where to plant trees can be based on many factors and the maps produced for this project are just one way of aiding decision making. Other maps are currently being produced to help determine the highest priority planting areas based on other criteria (e.g., protecting humans from air pollution; locations to improve energy conservation). These maps will be available from the OASIS web site in the future.

The various data produced for this project can provide significant benefits if used to help sustain or increase urban tree cover and health in New York City. The data provide information the amount of vegetation, some of the beneficial vegetation effects, available spaces to increase tree cover, and the spatial patterns of vegetation in relation to various artificial surfaces. It is hoped that managers in New York City utilize these data sets to help improve urban forest management and the urban forests effects on human health and environmental quality in the city.

Acknowledgments

References

Nowak, D.J., K.L. Civerolo, S.T. Rao, G. Sistla, C.J. Luley, and D.E. Crane. 2000. A modeling study of the impact of urban trees on ozone. *Atmos. Environ*. 34: 1601-1613.

Nowak, D.J., and D.E. Crane. 2000. The Urban Forest Effects (UFORE) Model: quantifying urban forest structure and functions. In: Hansen, M. and T. Burk (Eds.) *Integrated Tools for Natural Resources Inventories in the 21st Century*. Proc. Of the IUFRO Conference. USDA Forest Service General Technical Report NC-212. North Central Research Station, St. Paul, MN. pp. 714-720.

Nowak, D.J. and D.E. Crane. 2002. Carbon storage and sequestration by urban trees in the United States. *Environ. Poll*. 116(3): 381-389.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra. 2002a. Brooklyn's Urban Forest. *USDA Forest Service Gen. Tech. Rep. 290*. 107 p.

Nowak, D.J., D.E. Crane, and J.F. Dwyer. 2002b. Compensatory value of urban trees in the United States. *J. Arboric.* 28(4): 194-199.

Nowak, D.J. and J.F. Dwyer. 2002a. Urban forest structure and value at the national scale. *Proc. of the National Urban Forest Conference*. Washington, DC. p. 24-25.

Nowak, D.J. and J.F. Dwyer. 2002b. Assessing the value of urban forests in the United States. In: *2001 Society of American Foresters National Conference Proceedings*. Denver, CO. p. 237-241.

Nowak, D.J., P.J. McHale, M. Ibarra, D. Crane, J. Stevens, and C. Luley. 1998. Modeling the effects of urban vegetation on air pollution. In: Gryning, S.E. and N. Chaumerliac (eds.) *Air Pollution Modeling and Its Application XII*. Plenum Press, New York. pp. 399-407.

Nowak, D.J. and P. O'Connor. 2001. Syracuse urban forest master plan: guiding the city's forest resource in the 21st century. *USDA Forest Service General Technical Report*. 50 p.

Nowak, D.J., J. Pasek, R. Sequeira, D.E. Crane, and V. Mastro. 2001. Potential effect of *Anoplophora glabripennis* (Coleoptera: Cerambycidae) on urban trees in the United States. *J. Econon. Entomol*. 94(1): 16-22.

Appendix – UFORE Methods

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). 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.[5]

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

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[5]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.

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 midvalue 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).

Compensatory Value

The value of the trees in Baltimore was based on the compensatory value of trees as determined by 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 height of 1.37 m), 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 ($6.59/cm^2 for Maryland) 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:
$$BV = RC + (BP \cdot [TA_A - TA_R] \cdot SF)$$
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):
$$ATA = -0.335d^2 + 176d - 7020$$
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:

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

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

Volatile Organic Compound (VOC) Emissions

VOC 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 (Appendix A) to produce emission levels standardized to 30°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 (order and superorder values were used on 18.9 percent of the total leaf biomass). 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:

$$E = B_E \cdot B \cdot \gamma$$

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

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

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:

$$\gamma = \exp[\beta(T - T_S)]$$

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^o to 1.0^oC, 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 emissions during the in-leaf season to account for tree effects on air temperature and its consequent impact on VOC emissions.

Carbon Storage and 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 (Nat. Res. Counc. 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 (Table 2). For large trees (> 94 cm d.b.h. for hardwoods and > 122 cm d.b.h. for softwoods), volumetrically based equations were used to estimate biomass (Hahn 1984) based on the assumption that merchantable height was 80 percent of total tree height.

Biomass equations differ in the portion of tree biomass that is calculated, whether fresh or oven-dry weight is estimated, and in the diameter ranges used to devise the equations (Table 2). Equations that predict above-ground biomass were converted to whole-tree biomass based on a 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 d.b.h. (Nowak 1994b). To adjust for this difference, biomass results for urban trees were multiplied by 0.8. As deciduous trees drop their leaves annually, only C stored in wood biomass was calculated. For all biomass equations that included leaves, leaf biomass was removed from the estimate of total tree biomass based on equation comparisons of leaf biomass as a percent of total biomass by d.b.h. class. For evergreen trees, leaf biomass as calculated by UFORE-A was added to the estimate of total wood biomass to yield total tree biomass.

Because the use of multiple equations creates disjointed tree biomass estimates between equation predictions at various tree diameters, the equation results for individual species were combined together to produce one predictive equation for a wide range of diameters for various individual species. If there was no equation for an individual species, the average of results from equations of the same genus or hardwood/conifer group was used. 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. 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 were used. If no genus equations were found, the average of results from all broadleaf or conifer equations was used.

Total tree dry-weight biomass was converted to total stored C by multiplying by 0.5 (USDA For. Serv. 1952; Chow and Rolfe 1989). 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). Standard errors given for C report sampling error rather than error of estimation. Estimation error is unknown and likely larger than the reported sampling error. Estimation error also includes the uncertainty of using biomass equations and conversion factors, which may be large, as well as measurement error, which is typically very small.

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.

Growth rates were adjusted based on tree condition. For trees in fair to excellent condition, 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.

Air Pollution Removal
UFORE 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 from New Yrok City for 2000.

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}):

$$F = V_d \cdot C$$

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):

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

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

$$R_a = u(z) \cdot u_*^{-2}$$

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

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

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):

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

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

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

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^0); and N = fraction of opaque cloud cover (Venkatram 1980; EPA 1995). Under stable conditions, u_* was calculated by scaling actual windspeed with a calculated minimum windspeed based on methods given in EPA (1995).

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

$$R_b = 2(Sc)^{\frac{2}{3}}(\text{Pr})^{-\frac{2}{3}}(k \cdot u_*)^{-1}$$

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:

$$1/R_c = 1/(r_s + r_m) + 1/r_t$$

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 LAI and percent tree and shrub leaf area that is evergreen from the field data 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 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 (if any) 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 the 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.

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

$$I_x = R_t \cdot (LA_x / LA_t) / N_x$$

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).

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