A Report to North East State Foresters Association

A Plan to Integrate Management of Urban Trees into Air Quality Planning

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Figure 1 A massive smog episode in New York City in 1963. Photo: AP/Wide World. Photo Source: EPA Journal Jan/Feb 1990. EPA clean air standards implemented through State Implementation Plan (SIP) programs have resulted in a dramatic improvement in air quality in subsequent years. However, the region around New York City is still a non-attainment area for ozone, a major constituent of smog.

Executive Summary

This plan was developed by members of the Davey Resource Group, the New York State Department of Environmental Conservation, and the USDA Forest Service's Northeastern Research Station (Syracuse, New York). Funding was provided by a grant from the USDA Forest Service through the North East State Foresters Association.

The objective of the study is to provide technical evaluation, documentation, and general programmatic information on the strategy for the increase of urban tree cover as a means to improve air quality. The study used the urbanized area of New York City as an example, and identifies the following points:

- A study domain of 12,896 km^2 was established around the New York City ozone non-attainment area.
- Land use and cover data were determined through photo interpretation of digital orthoquad photographs in conjunction with multi-resolution land cover (MLRC) consortium data.
- Available surface area for additional tree planting in the urban areas of the study domain was determined to be about 1628 km^2.
- A base case scenario was developed for the urban cells with the meteorological model MM5 and photochemical model MODELS-3/CMAQ for July 12-15, 1995, to determine the effect of three levels of canopy increase in air quality: base case (existing level), reasonable (base + 10%), and maximum (base + 32%).
- For both 10% and 30% increase in canopy, the model predicted a maximum domain-wide drop of about 4 ppb of ozone (132 ppb to 128 ppb) for that period.

However, the areal extent of improvement is found to be dependent upon the extent of increase in the canopy cover.

- A review of the EPA policy memorandum on voluntary source emission reduction programs suggests that the strategy of increasing canopy cover to reduce ozone could be adopted, provided some variances to the current policy are accepted.
- Canopy increase can be promoted through a variety of approaches, including:
  - New tree planting
  - Augmenting growth of existing canopy
  - Reducing canopy mortality or loss
  - Education, public relations, and other indirect programs
- Each of the above approaches supports multiple programs that are outlined here in broad terms. Evaluation of these approaches and selection of programs to increase canopy cover and reduce air pollutants within each approach remains the task of individual States as they develop their plans to meet and maintain the National Ambient Air Quality Levels.

Acknowledgements

We gratefully acknowledge the funding provided by the USDA Forest Service through the North East State Foresters Association for this project. We further recognize that this plan is the product of the State, Federal and private agencies listed below, and represents their general consensus. However, the plan should not be considered as a policy or position statement for any particular group or governmental agency:

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Introduction/Project Description

Background

Recent research (Taha, 1996; Nowak et al., 2000; Civerolo et al., 2001) has substantiated the role of urban trees in improving air quality over New York and the Northeast. However, managing urban vegetation as a viable mechanism to improve air quality has not been fully investigated by State or Federal regulatory agencies. Discussions with the Environmental Protection Agency (EPA) and New York State Department of Conservation Division of Air Resources (DEC-Air) suggests that increasing tree canopy cover to reduce ground level ozone has the potential to be considered as a viable strategy as the agencies proceed with the development of procedures and policies for meeting and maintaining the ambient air quality through implementation plans. Thus, the challenge will be to develop a sound urban tree management strategy that could be fit into the current regulatory environment as a pollution control technology (e.g., tons of pollution removal) (Luley, 1998). An important part of this strategy will be to evaluate how land use and land cover can be integrated into air quality management along with urban forest management.

A valuable advantage of this approach would be the additional accrual of other environmental benefits that are due to increase in the urban tree cover, such as greenhouse gas emission reductions, protection of water resources, reduction of urban heat island effect, and the concomitant reduction in air conditioning usage, as well as many other benefits.

Overview

The goal of this project was to develop a plan to evaluate the feasibility of including management of urban vegetation in the air quality planning process. The study will address the potential of this approach from a technical, regulatory and programmatic perspective, with New York as an example. Further, this study could serve as technical reference and guidance for developing future documents or discussions, both at the state and federal level.

The study considered the ozone non-attainment area of the New York City metropolitan area, that includes portions of northeastern New Jersey and southwestern Connecticut (see Figure 2), to investigate the following four tasks:

1. Determining the potential for increasing tree canopy cover in the study area, i.e., quantifying existing tree canopy cover, open space for planting trees, and reasonably achievable tree canopy cover increases.
2. Computer modeling of the air quality and other associated beneficial impacts due to increasing tree canopy cover and the resulting improvement in air quality
3. Evaluating the likelihood that the increase in tree canopy cover is a viable strategy to improve air quality within the framework of the current regulatory environment.
4. Outlining potential strategies to achieve the projected increases in tree cover with associated improvement in air quality, and making recommendations to guide future work

Figure 1.

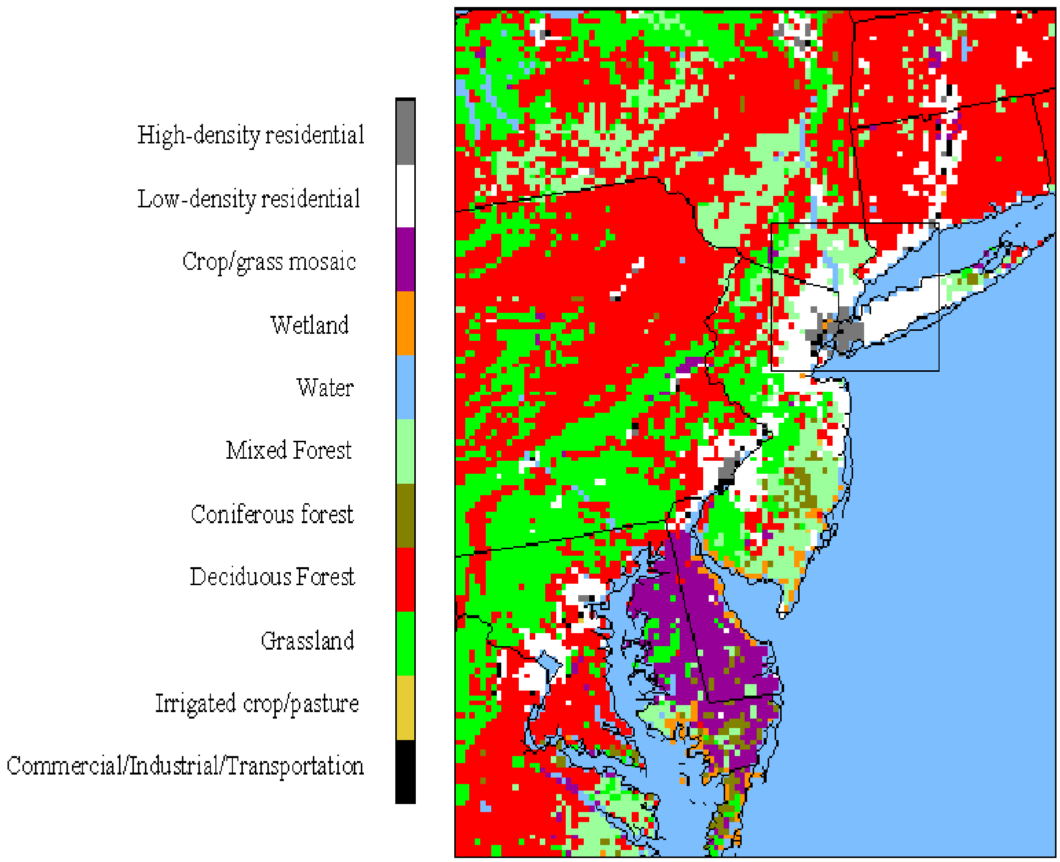

Figure 2 Modeling domain for the project to improve air quality by increasing tree canopy cover. The domain is defined by the box outlining the NYC metro area including parts of New Jersey and Connecticut. Source: Civerolo et al, 2001.

Importantly, we recognize that this study is an initial step in the process to assess environmental quality in a holistic manner by incorporating land use (increased tree canopy) into air quality improvement.

Figure 3 New York City and the surrounding region by night, seen from space. The high population density evident in this photo is closely related to air quality issues. Source: SpaceLink (http://spacelink.nasa.gov/NASA.Projects/Human.Exploration.and.Development.of.Space/Human.Space)

Methods

The methodology used in this study will be presented according to the four tasks outlined in the previous section.

<u>Task 1. Determining the potential for increasing tree canopy cover in the study area.</u>

A. Quantification of canopy cover and growing space

Quantification of the canopy cover and growing space available for planting was accomplished by delimiting boundaries of ozone non-attainment area in a geographic information system (GIS) format. The same grid format was also used for atmospheric modeling as described later. Each grid cell was 16 km^2 in size. Land use was defined by Multi-Resolution Land Class (MRLC) data for each grid cell (Table 1). Based on MRLC data, the study area (Figure 2) was divided into six strata in addition to New York City: urban – Long Island; rural – Long Island; urban – Hudson Valley; rural – Hudson Valley; urban – New Jersey; rural – New Jersey. Within each stratum, five digital orthoquad photographs (Landsat) were interpreted at a sample rate of 360 points per photo for a total of 1,800 points per stratum and 10,800 points overall. Aerial photos were overlaid on MRLC classifications and interpreted to determine average tree cover, pervious, open ground space (e.g., grass/soil), and impervious ground cover (e.g., buildings, pavement) within each MRLC cover type for each of six strata (see Appendix C).

New York City itself was not included in this analysis, as we had previously determined land use and tree cover data for New York City (Nowak et al., 2000), and merely incorporated those results into this project to produce the model domain described in Table 1. Photo interpretation results within each stratum and land use combination were merged into 4 km grid format ($16km^2$) using the GIS to match with gridded data used in atmospheric models.

MRLC Type	***Grids***	***Km^2***	***Acres***
Irrigated Crop/Pasture and Conifers	0	0	0
Wetlands	2	32	7907
Crop/Grass Mosaic	4	64	15,815
Commercial/Industrial/Transportation	8	128	31,270
Grassland	20	320	79,074
High-density residential	48	768	189,777
Mixed Forest	114	1,828	450,720
Deciduous Forest	119	1,904	470,488
Water bodies	229	3,664	905,393
Low-density residential	261	4,176	1,031,911
Total	806	12,896	3,182,355

Table 1. Identification of the MRLC grids classifications, the number of grids in each land use, and the land area in each type in the New York City domain used in the tree canopy analysis and ozone modeling. Acres rounded to nearest whole number.

B. Determining Tree Canopy Cover Increase

The amount of tree canopy cover that could reasonably be attained through various programs was determined by examining three potential sources:

(1) the amount of available planting space that would allow new tree planting by programs from both urban tree forestry and rural or traditional forestry;

(2) the existing tree cover that would increase in size due to canopy growth;

(3) the preservation of existing tree cover that would have otherwise been lost due to development or other causes.

Projections of potential canopy cover increases were based on numbers of trees that could reasonably be planted and survive over 30 years. In addition, growth projections for existing trees were based on historical growth rates for established trees (McPherson et al, 1994).

<u>Task 2. Computer modeling of the air quality and other associated tree benefit impacts due to increasing tree canopy cover</u>

A. Atmospheric Modeling of Air Quality Effects of Canopy Cover Increase

Atmospheric modeling for determining potential ozone reduction associated with increases in tree canopy cover was performed by the New York State Division of Air Resources (DEC-Air) as described in Appendix A. Briefly, the potential reductions of air pollutant concentrations from increased canopy cover were based on three tree canopy cover scenarios. These included:

- A base case representing existing vegetation cover as determined through photo interpretation
- A realistic case representing canopy cover increases that were identified as achievable on the ground through various programs and strategies
- A maximum case using the maximum increase in canopy cover that might be attainable given current land use and cover conditions. The differences in land cover are presented in Table 2.

Urban Land Use	*Base (Existing) Tree-Grass-Impervious*	*Realistic (Proposed) Tree-Grass-Impervious*	*Maximum Tree-Grass-Impervious*
Commercial-Industrial-Transportation	14%-34%-53%	24%-24%-52%	48%-0%-52%
Low Density Residential	33%-35%-32%	43%-25%-32%	68%-0%-32%
High Density Residential	25%-16%-59%	35%-6%-59%	41%-0%-59%

Table 2. Average percent cover of deciduous trees, grass and impervious surfaces in each of the three land use categories for the base, maximum and realistic MM5 ozone modeling simulations (from Civerolo et al, Appendix A).

General estimates to base land cover changes in the modeling were derived from the photo interpretation results from Task 1.

B. Other Environmental Benefits Associated with Canopy Cover Changes

Environmental benefits other than ozone reduction were calculated using the UFORE model as described elsewhere (Nowak and Crane, 2000).

Task 3. Evaluating the potential of the increase in tree canopy cover as a viable strategy to reduce ozone within the current regulatory environment.

A review of the potential for the increase in tree canopy and its modeling projections as an additional mitigation measure for ozone air quality was completed by DEC-Air. This review was based on a policy memorandum issued on January 19, 2001 from the EPA's Office of Air Quality Planning and Standards on incorporating voluntary source emission reduction programs into the SIP process (see Appendix B).

Task 4. Development of strategies to achieve the projected increase in tree cover and improvement in air quality, and to make recommendations on future work

Strategies for increasing tree canopy cover were developed after all data analysis for cover, available growing space, and ozone modeling was completed. These strategies were developed by consensus among the participants of the study. Existing strategies were derived from the methods, implementation, and success of planting programs around the country and abroad. Particular attention was paid to determining mortality rates for urban trees, since those rates drive many strategic decisions. Specific areas were examined included planting, preservation, maintenance, and education/public relations.

Results

Task 1. Determining the potential for increasing tree canopy cover.

The total study area is 3.19 million acres (12,896 km^2) in size based on 806 grid cells 16 km^2 in size (Table 1). The final study domain size, land classifications, and estimates for tree canopy increases were based on grid cell conversions from the MRLC database. MRLC classifications within the 4km grid were used for the final ozone modeling.

Results of the photo interpretation analysis (Appendix C) were used to assign cover data within the MRLC land cover type. Photo interpretation data and MRLC land use maps were combined using a GIS to determine cover and land use characteristics in 4km grid cells that were used for ozone modeling. Each 4km grid cell was represented by the dominant land use within each cell and its associated cover characteristics.

The photo interpretation provided data on cover type distribution within MRLC land use types (Appendix A, and displayed in Figure 4).

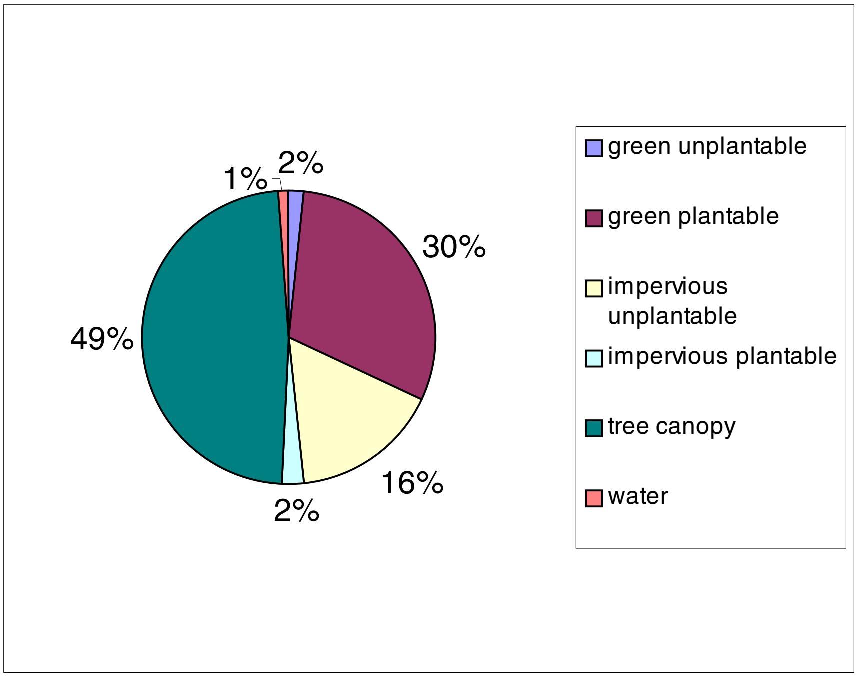

Figure 4 Land use in the New York City non-attainment area **as determined by photo interpretation.**

Projected Increase in Canopy Cover

Based on 4km grids, the maximum land area in the urban areas that could support an increase in tree canopy cover is 402,165 acres (1628 km^2) or 12.6% of the total land area in the modeling domain and 32.1% of the urban area. By consensus of the cooperating agencies, it was determined that a realistic increase in canopy cover was 125,300 acres (507 km^2) or 3.9% of the total land area in the modeling domain (10% in the urban land classifications). This 10% increase would result in a total tree canopy cover in the urban land classifications of 41%. Urban lands that were included in this classification were commercial-industrial-transportation, low density residential, and high density residential (Table 3)

Land Use	Total Urban Area Acres	Realistic Increase Percent	 Acres	Maximum Increase Percent	 Acres
Urban Commercial-Industrial-Transportation	31,300	10%	3,100	34%	10,600
Urban Low Density Residential	1,031, 900	10%	103,200	35%	361,200
Urban High Density Residential	189,800	10%	19,000	16%	30,400
Total	1,253,000	10%	125,300	32%	402,200

Table 3. Total land area in urban grid cells and the projected increases in tree cover for the realistic and maximum cases used in the MM5 modeling.

Task 2. Computer modeling of the air quality and other associated tree benefit impacts due to increasing tree canopy cover

A. Atmospheric Modeling of Air Quality Effects of Canopy Cover Increase

Differences in domain-wide daily ozone maximum between the maximum tree canopy increase (32%) and the base case were ~4 ppb (132 ppb to 128 ppb). Similar differences of ~4-5 ppb were found in domain-wide daily maximum between the realistic tree canopy increase (10%) and the base case), although the areal extent of improvement was larger in the maximum case (see Figure 5, and discussion in Appendix A). This similarity is probably due to the complexity of atmospheric dynamics and chemistry that precludes drawing a simple relationship between tree cover and ozone levels. The similar range of reduction in the ozone levels for the realistic and maximum cases suggests that canopy increases beyond base + 10% may not be needed if the criteria are limited to daily 1-hr ozone maxima. This suggests that a series of modeling runs may be needed to address the optimum level of increase in tree cover to provide the necessary ozone reduction. The potential impact on planting programs may be significant for even 1% change in canopy cover, since the number of trees is so large (see below and Appendix D).

Considerable variation in changes in ozone concentrations was found, depending on the location within the modeling domain (Appendix A). Modeling runs indicated that different locations within the domain could show either increases or decreases in ozone compared to the base case when changes in canopy cover occur (Figure 5).

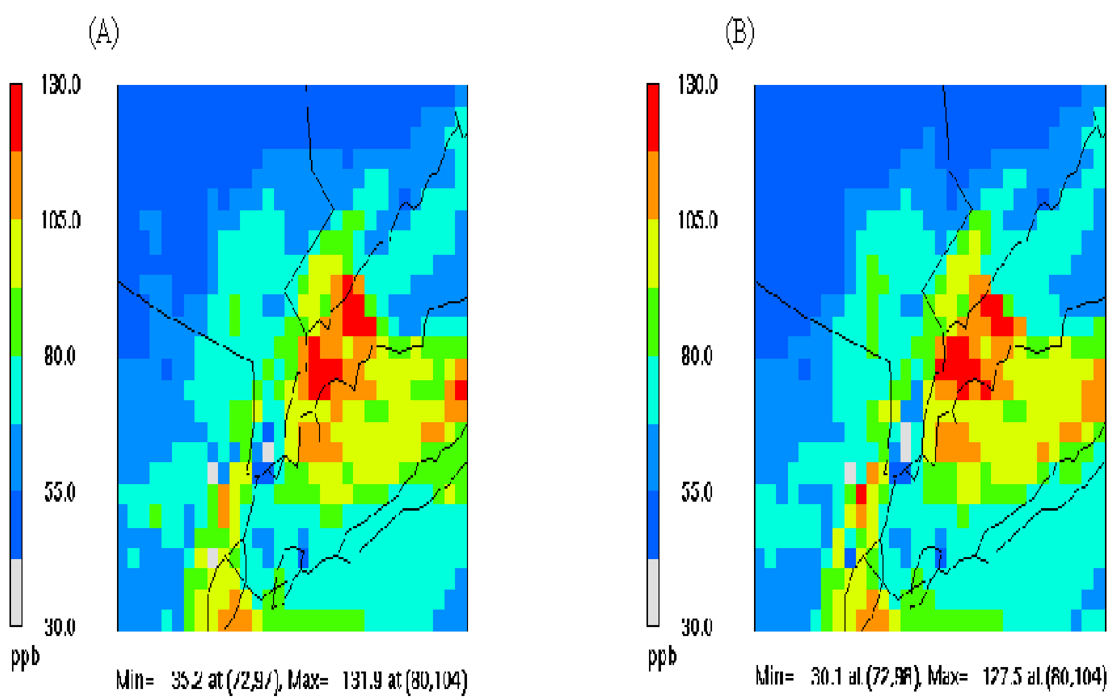

Figure 5 MODELS3-CMAQ results of July 15, 1995, with existing canopy (A) and realistic increased canopy (B), showing a reduction of daily ozone maximum by about 4 ppb. Source: Civerolo et al, 2001.

B. Other Environmental Benefits Associated with Canopy Cover Changes

Other air quality benefits associated with increased canopy cover are presented in Table 4. These changes in pollutant levels are based on increased tree cover of 200km^2, and demonstrate added benefit of reduction of other air pollutants as well.

Pollutant	*Metric Tons yr^{-1}*	*Metric Tons day^{-1}*	*Kg hr^{-1}*	*Metric Tons yr^{-1} per km^2 cover*
CO	216.9	1.1	48	0.4
NO_2	910.4	4.0	254	1.8
O_3	2070.6	10.2	687	4.1
PM 10	1323.8	5.5	240	2.6
SO_2	447.4	1.9	124	0.9
TOTAL	*4969.1*	*22.7*	*1352*	*9.8*

Table 4. Annual environmental benefits of additional tree cover of 200 km^2 under average 1994 conditions, as calculated by the UFORE model. ("PM 10" refers to particulate matter 10 microns or less in diameter).

Task 3. Evaluating the potential of increase in tree canopy cover as a viable strategy to reduce ozone within the current regulatory environment

DEC-Air reviewed a policy memorandum issued on January 19, 2001 by the EPA's Office of Air Quality Planning and Standards on incorporating voluntary source emission reduction programs into the SIP process, and their conclusions are presented in Appendix B. This review suggests that, in general, increasing canopy cover to reduce ozone may fall within this policy framework.

However, two important variances would need to be developed by the EPA. The first variance would be needed to alter the performance assessment of the voluntary program. Currently it is to be conducted no later than 18 months after initiation of the program, followed by re-evaluation every 3 years. The review process timing of 18 months and three years would be possible, but an extension would be needed to account for the longer time frame required for sufficient tree growth, since the time to reach full canopy increase and targeted air quality impact is estimated at 30 years.

A second variance would be needed because the voluntary programs requires that the State be responsible for assuring the emission reductions do occur as described in the SIP process. Under the proposed tree canopy increase program, it will not be possible to identify changes in emissions per se, as the proposed tree canopy may result in an increase or decrease in emissions due to increases in tree population or changes in ambient air temperature. However, demonstration of improved air quality from the program would be consistent with the SIP goal of meeting and maintaining national ambient air quality.

Task 4. Development of acceptable programs to achieve the projected increase in tree cover and improvement in air quality

Based on the modeling and regulatory analyses outlined above, potential mechanisms and programs to achieve the needed canopy increase were developed. Since this document is to be used as guidance for technical issues pertaining to the potential of increasing canopy cover and its impact on air quality, only broad general program descriptions are provided without specific references to operational level, funding or administration.

Other generic issues that impact this program, such as the technical treatment of land use and land cover changes in computer modeling scenarios, would need to be reviewed in detail and were considered to be beyond the scope of this document.

Figure 6 Ikonos image from space, showing the small amount of green space in and around New York City during the summer of 1997. Source: www.spaceimaging.com/ikonos/ NewYorkC_tm_250.jpg

Discussion

Integrating the management of urban tree canopy cover into the air quality process appears to be a potentially viable option based on:

- Atmospheric modeling that shows a ~4-5 ppb decrease in domain wide maximum ozone levels
- An increase in other tree-related benefits including greenhouse gas reductions, summer air temperature decreases, increased storm water protection, reduced air conditioning cooling loads, among others
- Potentially realistic canopy increase goal equal to 125,296 acres (507 km^2) or 3.9% of the land area in the modeling domain (10% of the urban land in the case of New York City).

The final task describes both conceptual and general programmatic outlines of the means to achieve the canopy increase projections in the study domain.

Conceptual Analysis of Increasing Tree Canopy Cover

Two important principles govern this discussion. To begin with, it is important to recognize that the new canopy cover can only come from two sources: growth of the canopy of existing trees, and canopy from completely new trees. A third source that is not from new canopy cover, but may be useful in reducing ozone, is the protection of existing canopy that would otherwise be lost due to development or other causes. In other words, the total canopy cover in the domain including projected increase can be expressed as:

(1) $$C_T = C_B + C_N + C_G - C_M$$

where C_T = total canopy cover in the modeling domain in 30 years, C_B = the existing tree canopy (base case), C_N = canopy increase from new tree planting, C_G = the growth of existing canopy, and C_M = non-urban canopy mortality or loss due to natural and man-induced causes. The goal under the reasonable scenario (+10% cover) is to have the base existing canopy (C_B) increase by 507 km^2 ($C_N + C_G - C_M$).

The C_N term (canopy from new trees) can come from many programs, as described below, some which include planting of trees on ground were no trees currently exist to tree planting to replace trees removed due to mortality or development. The contribution of natural sources of new trees in the urban domain is unknown and perhaps incalculable, but may be substantial. The permanent plots that have been set up for UFORE analysis will eventually yield reliable estimates of that contribution (Nowak and Crane, 2000).

C_G would come from increases in canopy size of existing trees over the current base in urban grids. These increases could be fostered by development of tree maintenance and educational programs that help preserve and promote the existing urban forest canopy.

Currently it is unclear how the preservation or prevention of loss of existing canopy will be treated from an operational and regulatory standpoint. However, canopy preservation through reduced mortality or reduced land change is a critical element in a proposed plan and programs to improve air quality. Efforts to reduce canopy loss would seem to be a common sense approach to improving or sustaining air quality in any State (represented in a conceptual manner in Figure 7). Yet there appears to be no regulatory precedent for dealing with the loss or preservation of existing tree canopy cover as it affects future air quality and air quality programs.

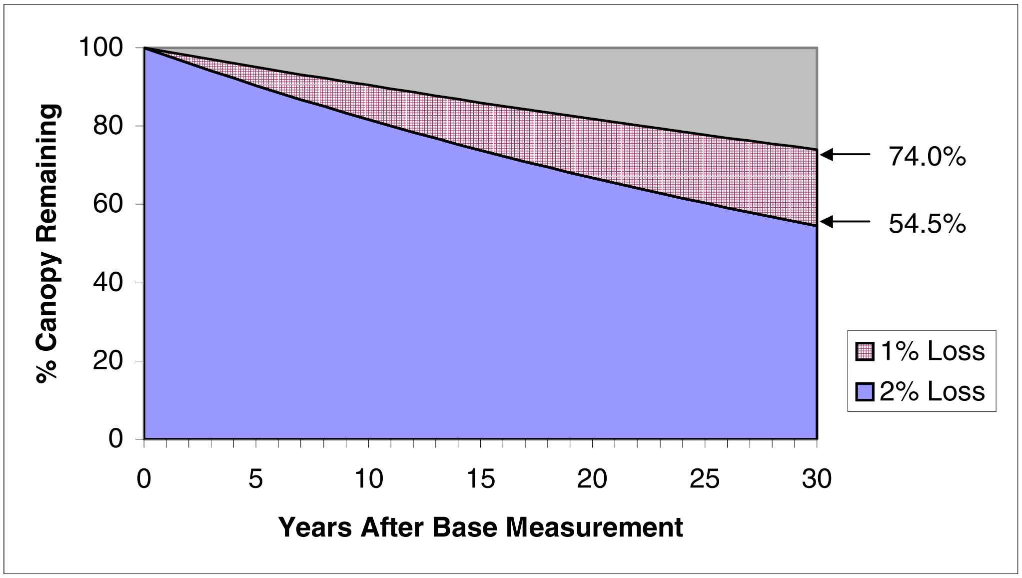

Figure 7 Schematic representation of the amount of functional canopy retained by halving a hypothetical annual loss rate of 2%. Red hatched area indicates functional canopy preserved for improving air quality, a difference here of about 20% after 30 years.

Conceptual Analysis of Programs to Achieve Canopy Increases

It is clear that no single program or approach can be expected to supply the desired canopy increases because the amount of new canopy required to obtain the projected improvement in air quality likely exceeds the capacity of any single method or program. Tree planting is projected to be an important, if not most important, means to increase canopy cover. However, depending solely on a planting program to achieve the canopy increase ignores other important elements of urban forest management (preservation and maintenance), and could be risky given the uncertainty about mortality rates.

The variety of land uses (both public and private), agencies, and land use managers, that might be directly involved in canopy increase projects also argues for multiple programs and administrators. Further, it is difficult to conceive of any single program that could satisfy the demands of canopy increase in a domain that ranges from inner-city to suburban communities, industrial to forested sites, and from individuals to corporate and public agents. Therefore, we believe that a variety of well-conceived programs that coherently work toward the same goal will provide the best insurance of attainment, and simultaneously ensure against unforeseen problems that could lead to worsening air quality and continued non-attainment.

Federally regulatory policy typically requires that even voluntary programs be verifiable and enforceable. The voluntary program that was reviewed in this study (Appendix B) contained such requirements. Three options are potentially available to verify and enforce the proposed canopy increases:

1. Remote Sensing. The first option could make use of space imaging (Landsat or another platform) or other form of digital aerial imaging. This approach would provide actual measurement of changes in canopy cover between specified time intervals. It would also potentially allow early, real-time verification that canopy increase goals were being achieved. However, such analysis of changes in urban vegetation cover would raise issues concerning the actual source of changes in canopy cover. Broad-scale assessments of changes in canopy cover in the study area could be conducted using Landsat images in a relatively cost-effective manner. However, it would be difficult to separate growth of existing vegetation, loss of existing canopy cover, and actual program-induced increase in canopy cover using broad-scale cover analyses. Another important aspect of this approach is to determine how remote sensing results would be treated from a regulatory standpoint if this method were used.

2. Program Verification. The second option would be to verify and enforce the existence and completion of programs that support various means to increase tree canopy cover. In essence, canopy increases would occur through a number of well-defined programs such as tree planting that would have specific funding and completion goals. Successful funding and completion of each program along with the projected accomplishments would be the basis of the verification and enforcement required. This approach could be labeled as a programmatic approach to verification and enforcement. Use of a programmatic approach would allow close accounting of the programs that were developed to increase tree canopy cover without the problems of remote sensing or the costs of field verification. However, this approach would only guarantee that the programs were in place, and may not ensure that the actual canopy increases have occurred on the ground.

3. Ground Truthing. The final approach would be to physically count the number of trees planted and surviving and to measure on the ground the changes in canopy growth. Although this could be accomplished through a predetermined sampling process, this approach will likely be programmatically difficult, as well as cost prohibitive, to physically enforce and field-verify the proposed canopy increases.

Ultimately, the best method may be some combination of the above approaches. Whichever approach is used, a determination of how to both measure and interpret changes in base canopy cover (i.e., that existing at the start of any program) will be needed to ensure that the projected canopy increase will occur.

General Outline of Programs to Increase Canopy Cover

This final section outlines the general types of programs that could be useful to increase tree canopy cover in the study domain to the required level. These programs need to be developed in detail and submitted for consideration to the regulatory agency.

While there is a broad range of types, number and varieties of different programs that might be developed to increase canopy cover, it should be noted that each program will likely fall under one of the two broad categories presented in the previous section: 1) planting or providing means for new trees, and 2) the preservation and growth of the existing canopy cover. A third group of programs, education and public relations would indirectly promote the goal of increasing canopy cover and is included here to complement the direct programs.

It is likely that the programs might be funded, administered and overseen by a variety of different agencies or organizations. A number of the programs may require legislative action to provide the legal and regulatory support to accomplish the programs goals.

C_{N} : Increasing New Canopy

Establishment of new trees is the most obvious and direct means to increase tree canopy cover. As determined in the aerial photographic analysis, there is ample open space in both urban and non-urban areas that could be used for new tree planting to accomplish the projected required increase in canopy cover (Appendices A and C).

The maximum land area in the urban grids of the study domain that could support an increase in tree canopy cover through tree planting is 402,200 acres (1628 km^2) or 12.6% of the total land area. By consensus of the cooperating agencies, we determined that a realistic increase in canopy cover was 125,300 acres (507 km^2) or 3.9% of the total land area (10% in urban grids) in the modeling domain. If tree planting were expanded to the other land use classifications, there is an estimated 1.04 million acres (4,209 km^2) that are open for planting.

If tree planting were the only program used to achieve the increase in canopy cover, we calculate that something like 1 million trees would have to be planted annually to reach this goal. This number varies with different assumptions about species composition, size of planting stock, and mortality rates (see below and Appendix D). Moreover, these estimates do not include any changes either in growth or mortality of the existing canopy cover, which is currently treated as a static resource.

The best strategy to meet the needed tree-planting goal appears to be to spread the tree planting among a number of diverse programs that use various sources of funding and means. This recognition leads to the following program descriptions:

General Program #1

Program Name: Tree Planting

Possible Administration: State

Possible Verification: Aerial photo analysis; tree counts; programmatic verification

Possible Funding: State; Polluters

Comments: Tree planting is likely to be the most generally accepted and popular program to increase tree canopy cover. Planting large numbers of trees will be a costly program if there is widespread response to the offer of tree stock or planting funds for municipalities and homeowners, or if large planting stock is used. Making tree-planting stock or funds available typically requires a high level of administration to ensure that trees are selected and planted properly, and that funds are used appropriately.

Tree planting could be useful and popular with a large number of agencies and organizations, including municipalities, non-profit organizations, commercial landowners and property managers, schools, colleges, universities, homeowners, industrial and commercial property owners, to mention a few. It is possible that some of these organizations, such as non-profit groups, could be key players in a large tree-planting program.

Tree planting to cover tree losses is another potentially viable program to increase canopy cover and decrease the impact of the loss of existing trees. These tree-planting programs could be used to offset losses due to development of existing tree-covered land or to replace trees that are lost through natural causes. Care would have to be taken to account sufficiently for reasonable mortality rates; a 1:1 tree replacement program, for instance, would mean an actual reduction in canopy because it did not factor in the predictable death of the replacement trees themselves, or the differences in canopy size.

New trees could also come through more natural means such as the conversion of currently mowed grass-covered land to wild or tree-covered land. Trees could be planted to accelerate the conversion, or the cessation of mowing could be used to allow natural inseeding, as has occurred on many farmlands in the Northeast wherever seed trees were close enough to populate fallow ground.

The greatest practical impediment to relying on tree planting as the primary strategy for canopy increase is the lack of reliable mortality data. Some data exist for street trees (e.g. Gilbertson and Bradshaw, 1990; Nowak et al, 1990; Ip, 1996; White, 2001), but the annual mortality rates reported vary widely (from 3 to more than 30%) and rely on data from only 3-4 years. Also, street trees make up only 3-10% of the urban forest (Miller,1997), and for the remainder there are few published data.

The few general mortality rates on urban street trees that exist suggest a variable mortality by size class from 2.1% to 5.4% (Nowak, 1986, McPherson et al, 1996). Using those numbers would require an annual planting of about 1 million trees for 10 years (Appendix D)—clearly a daunting task. Better mortality data on the entire urban forest will come with long-term results from the permanent plots currently being established by the

USFS. Until more and better data are available on this critical question, basing detailed policy on tree planting remains difficult.

In more general terms, it has been estimated that the general half-life of the urban forest is 20-30 years (Miller, 1997). Such a turnover rate suggests a 2:1 planting strategy is needed, i.e., planting two trees for every tree needed after 30 years. The high number of trees involved raises significant operational obstacles ranging from tree stock supply and cost, program administration, and planting logistics (see Figure 8). Planting costs, moreover, could range from $3 to $300 per tree, depending on whether seedlings (high mortality) or balled and burlapped trees (lower mortality) were used. Therefore, a planting program could cost from $4.2M (all seedlings, high mortality) to $750M (all B&B, lower mortality) per year. These costs do not include administration, verification, or enforcement expenses, and ignore such essentials as stakes, mulch and water for the first year. Such a range in cost clearly will have to be narrowed before the viability of tree planting within this context can be assessed.

Figure 8 The staging area for new tree planting following the ice storm of 1998 in northern New York.

Clearly these are just a few of the many potential programs that could be developed and administered to achieve the required tree-planting goal. The details of the specific programs would take careful planning and execution to minimize tree-planting costs and maximize tree survival.

C_G : Promoting Growth of Existing Canopy

The study domain contains already 463,000 acres of urban tree cover and urban grass, and about four times more tree cover is found in rural forest (Appendix A). Over a 30-year period, that existing canopy will increase, especially in urban settings where trees tend to be open-grown. The increase of existing canopy could make a significant contribution to the desired increase in canopy cover. The primary means for increasing existing urban tree canopy growth will be through maintenance of existing tree, preservation of existing canopy and education on the importance of tree canopy cover to air quality and proper tree maintenance.

Consideration of the accounting for growth and loss of existing canopy cover will need to be made before programs can be developed. Canopy growth could be considered over the base without counting the loss of the base, or it could be counted as a net growth with the loss of the existing base being accounted for.

Potential increases in canopy size can be projected from the existing size, composition and mortality of the current urban forest. Available data were used to make reasonable estimates of canopy growth in the urban areas that were modeled for canopy increases.

General Program #2

Program: Maintenance of Existing Canopy to Promote Tree Growth

Possible Administration: State

Possible Verification: Aerial photo analysis; programmatic verification

Possible Funding: State; Polluters; Property owners

Comments: Incentives for maintenance programs for existing trees will be useful to ensure that canopy increases will occur. Many communities and property owners already have existing maintenance programs that could be supplemented to extend any funding for tree maintenance.

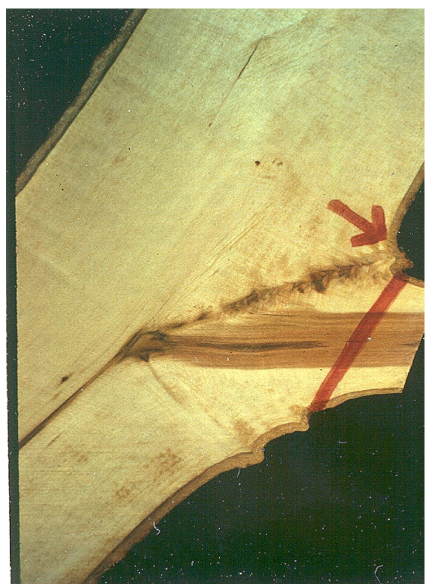

Figure 9 Making pruning cuts at the proper location substantially improves the long-term health of maintained trees. Source: Alex Shigo

Funding for maintenance of publicly managed trees should specifically be included, possibly as a separate program. Public trees are an under-managed segment of the existing canopy cover. Although tree cover from public trees is usually less than 10% of the total tree cover, management of these trees can serve as a highly visible, positive example to the private tree owner.

C_M = Canopy mortality or loss due to natural and human-induced causes

Protection of existing canopy from loss through human-induced or natural causes is presented as an alternative program until it is clear how loss of the base (existing) canopy will be treated from a regulatory standpoint. From an air quality standpoint, loss of the base canopy could have significant air quality impacts and could offset any increases in canopy that occur from other programs. Loss of the existing base would also decrease or offset potential increases in canopy growth of the base. Protection of the existing canopy could be achieved through a number of programs. Some states, such as New Jersey (http://www.njleg.state.nj.us/2000/Bills/al01/10_.pdf), have programs already in existence to reduce losses of the existing canopy cover.

Figure 10 Even a minimal Tree Protection Zone (this one is substandard) during construction can significantly affect the survival of mature trees during human landscape change.

General Program #3

Program: Protection of Existing Canopy

Possible Administration: State and or Local (County, town, city, or village)

Possible Verification: Aerial photographic analysis; Programmatic

Possible Funding: State and or Local

Comments: One of the most powerful means to ensure that air quality will be maintained and increases in canopy cover will occur will be to protect the existing urban forest from removal. Reducing canopy loss will be the most difficult to achieve by using a broad programmatic approach. Local governments will be important in this regard as they can enact and enforce local ordinances that protect existing vegetation and can require replacement of any trees that are removed. In fact, many of these ordinances are in place in communities in the Northeast and around the country, and excellent means have been published on the web to help communities develop such ordinances (http://www.isa-arbor.com/tree-ord).

Education, Public Relations and Marketing Programs

Education and public relations and marketing programs should be considered as key elements in preserving, maintaining and increasing canopy cover. Education, public relations and marketing should probably be developed as separate program areas. Education could focus primarily on smaller scale programs that focus on proper tree selection, planting, maintenance, preservation and care. This education is an essential supplement to any program depending on successful tree planting, as projected mortality rates for newly planted trees are over 50% after 30 years. These programs could be developed and administered by cooperative extension, State forestry organizations, or other local agencies. Although education can be broader scale in delivery, it may be better accomplished through larger scale public relations and marketing efforts.

Public relations and marketing would deal with broader media approaches covering more general issues such as the importance of urban trees to air quality, the importance of tree planting, maintenance and preservation, and "how get involved" type of messages. These efforts would be developed for delivery to larger numbers of people through mass media and other broad-scale means. Clearly, the administration and execution of these public relations and marketing would be significantly different than a more local delivery of educational programs.

General Program #4

Program: Education on Tree Planting, Maintenance and Preservation

Possible Administration: State Forestry; Cooperative Extension, Private Industry

Possible Verification: Based on use of allotted funding and/or contact training hours.

Possible Funding: Urban and community state and federal funds; polluters;

Comments: Although the impact on canopy preservation, maintenance and tree planting will be difficult to measure, a well defined and executed education program could be one of the strongest components of this overall strategy. The public has the largest ownership share of the existing canopy cover. Educating the public on both the value of the tree cover to improve air quality and the importance of proper tree planting, maintenance and preservation will be critical to increasing and preserving of the existing canopy cover. The infrastructure for education programs is already in place through the State Forestry and Cooperative Extension office. Frequently, experts in private industry play a key role in the delivery of educational programs developed by public agencies.

General Program #5

Program: Public Relations Campaign on the Importance of Trees to Air Quality and on the Maintenance and Preservation of Existing Canopy

Possible Administration: State Forestry

Possible Verification: Based on use of allotted funding and messages delivered

Possible Funding: Polluters

Comments: Large-scale, multi-media marketing approaches that cover the importance of trees to air quality and tree maintenance and preservation messages, could have a similar effect as smaller scale education programs in encouraging the maintenance and preservation of existing canopy cover. This approach could fit well for funding from large-scale polluters that may be looking for a positive ad campaign.

Summary and Conclusions

This study provides both technical and regulatory documentation and evaluation supporting additional efforts to integrate the management of urban tree cover into federal regulatory programs to improve air quality. Based on the results of this analysis, the participants involved in the development of this study agree that further investigation is needed to better understand the effects of increased canopy to improve air quality. This is based on (1) the potential to reduce ground level ozone by 4-5 ppb through a modest increase in tree canopy cover, (2) presence of ample open space in urban areas to achieve these canopy increases, (3) a substantial increase in other environmental benefits associated with the increase in canopy cover, and (4) the potential acceptance of the canopy increase as a measure under the voluntary program.

Programmatic recommendations to achieve the desired canopy cover increases and air quality improvements are presented in this plan. These programs outline general approaches that could be used to increase canopy cover. A number of significant issues, such as the accounting for changes in existing canopy cover and land use, will require further assessment before more definitive approaches to increasing canopy cover can be developed.

Finally, this document is intended to serve as general technical support and reference for additional efforts to integrate management of urban vegetation into air quality improvement programs.

Disclaimer

This study is not a reflection of the policies or practices of the participating organizations nor or the funding agencies.

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Appendix A

Effects of Increased Vegetation on Ozone Air Quality in the New York Metropolitan Area

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1. Introduction

The New York State DEC has performed a series of high-resolution photochemical modeling simulations to investigate the role of urban vegetation on ozone air quality in the New York City metropolitan area, for the mid-July 1995 episodic period. The near-surface meteorological fields, biogenic NO and VOC emissions, and O_3 results are summarized in the following sections. Preliminary results indicate that there is an improvement in the ozone air quality from the increased population of trees in the urbanized portions of the region as well as other ancillary benefits such as lower air temperatures.

2. Meteorological modeling scenarios

The meteorological model used for this project is the 5th Generation Penn State University/NCAR Mesoscale Model (MM5 Version 3.4; Dudhia, 1993). The 4-km domain is shown in Figure 1, consisting of 111 east-west grids and 153 north-south grids, with the domain centered on New Jersey. The meteorological simulation covers the period from July 12 (12Z) to July 17 (12Z), 1995. For these simulations, the model utilizes 32 terrain-following vertical levels, extending to ~16 km, with the lowest level about 9 m above ground. Four-dimensional data assimilation was not used, since we wanted to examine the effects arising from the different land surface processes and parameterization metrics. The base case land use/land cover data, based upon very high resolution satellite data, were provided to us by the U.S. Forest Service (Nowak, 2001). The planetary boundary layer (PBL) scheme used in these simulations was the Blackadar high-resolution PBL (e.g. Zhang and Anthes, 1982).

The surface parameterizations for the land use categories for the base case simulation are listed in Table 1. The default version of MM5 utilizes only a single urban land use category, which is assumed to be representative of all urban areas. However, such an approach needs to be modified in this study to enable differences in land use that are apparent in different urban grid cell(s). Therefore, in this study, we created three separate urban land use categories – *low-density residential*, *high-density residential*, and *commercial/industrial/transportation*. For these categories, we assumed that three different cover types to adequately describe each land use category – deciduous trees, grass, and impervious surfaces. Based upon aerial photography and ground-truthing in cities in the northeastern U.S., the percent areal cover in a grid cell were developed by the the Forest Service (Nowak, 2001) and are listed in Table 2 for the Base case simualtion. Once these areal covers were known, we constructed new area-weighted surface parameterizations based upon literature values (Pielke, 1984). The improved urban roughness length (z_0) values were taken from Stull (1994), and no areal weighting was performed on z_0 in any of the simulations. For the remaining 10 land use categories in the model, we used the appropriate PSU/NCAR (13 categories) or USGS (25 categories) values.

In addition to the base case land use file, we generated two additional land use files, based upon proposed future tree cover scenarios. In the "maximum" scenario, we converted all of the urban grass cover to deciduous tree cover. This represents an absolute upper limit on the tree cover in an urban land grid, assuming that impervious surfaces (houses, roads, parking lots, etc.) would remain unchanged. In the more "realistic" scenario, only a fraction of the urban grass cover was converted to deciduous tree cover. Table 2 lists the percent areal cover by urban land use category for these two scenarios.

3. Emissions modeling scenarios

3.1 Anthropogenic emissions

The anthropogenic emissions of CO, NOx, and VOCs were processed with the Emissions Modeling System (EMS-95; Emigh and Wilkinson, 1995) to provide gridded, hourly speciated data. Anthropogenic emissions are comprised of three principal categories: area sources, motor vehicle sources, and point sources. The emissions inventory data used in this study were adapted from the Ozone Transport Assessment Group (OTAG, 1996) to generate typical weekday and weekend day emissions for the July 7-18 episodic period. In this analysis, we did not distinguish between elevated and low-level point sources, and utilized temperature data from the base case MM5 simulation to estimate motor vehicle emissions, thus generating a single set of anthropogenic emissions for use in the photochemical model simulations.

3.2 Biogenic emissions

The biogenic emissions were computed with the Sparse Matrix Operator Kernel - Biogenic Emissions Inventory System (SMOKE-BEIS2; Houyoux et al., 1996). SMOKE-BEIS2 calculates hourly gridded emissions of aldehydes (ALD2), isoprene (ISOP), nitric oxide (NO), olefins (OLE), and paraffins (PAR). The model requires species-specific gridded vegetation cover information, species-specific BEIS2 normalized emission rate factors, and surface-layer temperature and shortwave radiation fields. The vegetation cover was obtained from Jim Wilkinson (Alpine Geophysics), and consists of the areal extent of rural forest, urban forest, agricultural land, and "other" land (which includes water, urban land, and barren land) in each grid cell. The temperature and radiation fields were extracted from the base case MM5 simualtion. For the input temperature, we took the average of the ground temperature and the temperature at the lowest level (~9 m) to be more representative of the temperatures in the vegetated surface layer.

We performed three sets of biogenic emission scenarios, in which we modified the vegetation cover, temperatures, and radiation fields, corresponding to the three MM5 simulations, for July 13-15. For the maximum tree case, we converted all of the existing grass cover in the 975 urban cells to the BEIS2 urban tree (Utre) category, which consists of 50% hardwood forest and 50% coniferous forest. For the realistic tree case, only 30% of the existing grass cover in the urban cells was converted to the Utre category. The Utre category is a moderate VOC-emitter, having a normalized isoprene emissions rate of 5140 $\mu g\ m^{-2}\ hr^{-1}$. For comparison, the normalized isoprene emissions rate is 56.2 $\mu g\ m^{-2}\ hr^{-1}$ for grass, and 29750 $\mu g\ m^{-2}\ hr^{-1}$ for Quercus (oak). However, Nowak et al. (2000) showed that the tree species composition had no detectable effect on predicted O_3 concentrations in the anthropogenic emissions-rich northeastern U.S. urban corridor.

4. Photochemical modeling scenarios

The photochemical model applied in this study was the EPA MODELS-3 Community Multiscale Air Quality (CMAQ) model (Byun and Ching, 1999), using the Carbon Bond IV mechanism. CMAQ predicts gridded hourly concentrations of numerous gas-phase and speciated aerosol compounds. In this study, we simulated the July 13-15 period, allowing for the first two days as the "spin-up" days. The CMAQ horizontal grid structure followed that of MM5, and in the vertical the model was limited to 16 vertical levels, identical to the lowest 16 levels in MM5.

5. Analysis of meteorological fields

5.1 Spatial patterns

In the following discussions, the focus will be on area centered about the New York City metropolitan area, and this is identified in Figure 1. The surface temperature data at 20Z on July 15 for the base case is displayed in Figure 2A; the differences between the base and maximum cases in Figure 2B; and the differences between base and realistic cases in Figure 2C. In a similar way, the relative humidity data are displayed in Figures 3A through 3C. For the maximum case, the largest temperature decreases and largest humidity increases are found to occur downwind of the NYC urban core area of coastal Connecticut and the Long Island Sound region, similar to the findings of Civerolo et al. (2000). In the Bronx and Manhattan area, the afternoon relative humidity increased by about 3-15% in the maximum case (from base case values of about 30-45%), and the afternoon temperatures dropped by about 0.5-3.5° C (from base case temperatures that are 33ºC or higher). To assess the effect of the sceanrios over the day, we focus on two grid cells – one in upper Manhattan, and one near Bridgeport, CT- in the next section.

5.2 Time series

Figures 4A-E show the time series of surface temperature, relative humidity, wind speed, wind direction, and PBL height, respectively, for the three cases at the Manhattan grid cell on July 15. For these prognosed meteorological variables, the differences were generally small between the three scenarios. The maximum case temperatures were about 1ºC lower during the afternoon hours (see Figure 4A), and the maximum case relative humidities were a few percent higher than the base case (see Figure 4B). The differences in wind speed were less systematic (see Figures 4C and D).

The MM5 simulations utilized the option of Blackadar method for estimating the PBL heights. However, these estimates are very sensitive to surface stability, and are prone to abrupt jumps. This is a limitation of the PBL scheme, which does not take into account the potential of entire PBL to support vertical mixing. Therefore, in this study, the daytime PBL heights were re-computed based upon the potential temperature profile regardless of the surface stability regime, while the nighttime PBL collapsed to the top of the lowest layer (~18 m). On July 15, the afternoon PBL heights were generally lower in the maximum case, compared to the base case, after 18Z (see Figure 4E).

The corresponding time series for the CT grid cell are shown in Figures 5A-E. Qualitatively, the results are similar to Figures 4A-E. Note that on July 15, the maximum case PBL heights were about 300- 400 m lower than the base case (see Figure 5E). However, at this grid point it is difficult to separate out the effects of the land use changes from the influence of the Long Island Sound.

5.3 Vertical profiles

The vertical profiles of temperature and relative humidity at the two grid locations are shown in Figures 6 and 7. Although the differences between the model runs are smaller for the

Manhattan grid cell (see Figure 6), it is clear that the largest differences are not simply confined to the lowest layer. Throughout much of the PBL, temperature differences of 1-5º C and relative humidity differences of 10-30% are possible, especially downwind of the core NYC metropolitan area (see Figure 7).

6. Analysis of biogenic emissions

Table 3 lists the total biogenic emissions by species on July 15 within the NYC analysis subdomain. Note that the emissions of ISOP and PAR are more than an order of magnitude larger than those of NO, OLE, or ALD2. For comparison, the corresponding area and motor vehicle emissions of NO, PAR, OLE, and ALD2 are listed in Table 4. Clearly, biogenic NO is swamped by the anthropogenic emissions in this area. Additionally, the area and motor vehicle emissions of toluene, xylene, ethane, and ethanol were each about 1×10^6 moles on this day. Clearly, the biogenic ISOP and PAR contribute appreciably to the VOC burden in this region.

Figure 8 shows the spatial pattern in ISOP emissions at 17Z on July 15 for the (Figure 8A) base case, and the differences between the base and sensitivity cases (Figures 8B and C), defined as "base case minus sensitivity case". In the maximum case, the ISOP emissions decreased over much of Long Island (except for a few grids along the Atlantic shore), while ISOP increased a little farther inland (see Figure 8B). The emission changes were much smaller in the realistic case (see Figure 8C). In both of the sensitivity cases, the changes in ISOP emissions in the core NYC urban areas were very small. This is not surprising, since there are simply many more trees in the outlying urban or semi-rural areas in the region.

While the absolute biogenic emissions of ISOP and PAR are substantial in this region, the two sensitivity simulations resulted in very small increases in biogenic emissions, generally on the order of 4% or less (see Table 3). The ISOP emissions increased negligibly compared to the base case (even the maximum case), while the PAR, OLE, and ALD2 emissions increased by about 1-4%. The biogenic emissions of NO decreased slightly, but are roughly two orders of magnitude smaller than the anthropogenic NO emissions in this region. Hence, in terms of the biogenic emissions, the increased urban tree cover resulted in a negligible change of biogenic NOx and VOC emissions.

7. Analysis of predicted O_3 concentrations

Figure 9 shows the results from the base case and maximum case CMAQ simulations. The panels in Figure 9 show the daily maximum predicted O_3 concentration for the base tree cover case, the maximum tree cover case, and the difference between the two cases (base minus maximum). Note that in the NYC metropolitan region, the maximum tree planting scenario resulted in a ~4 ppb reduction in the predicted domain-wide daily maximum (~132 ppb to ~128 ppb). The spatial patterns of these two simulations are very similar, exhibiting the highest concentrations over Long Island Sound. However, the increased urban tree cover actually resulted in increased O_3 levels in northern New Jersey, west of Manhattan and Brooklyn. While the largest reductions (grid cell-by-grid cell differences) in daily maximum O_3 also occurred in the region of highest concentrations, and could be as high as about 60 ppb, the net effect of the urban tree planting was to increase O_3 in some places and decrease O_3 in others.

Figure 10 shows the same information for the base and realistic tree cover scenarios. Note that the two simulations, again, produced similar spatial patterns, although the grid-by-grid differences were smaller than the corresponding differences for the maximum tree case. However, the domain-wide daily maximum O_3 concentration again decreased by about 4-5 ppb. This suggests that even a moderate increase in tree cover may help reduce the maximum O_3 levels in this region. If a predicted domain-wide NAAQS design value of about 130 ppb is representative of that which is actually observed in this region, a 4-5 ppb decrease represents a substantial step toward attainment of the 1-hour O_3 NAAQS.

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Table 1. Surface parameterizations for the base MM5 simulation.

Landuse category	Shortwave albedo (%)	Moisture availability (%)	Longwave emissivity (%)	Roughness length (cm)	Thermal inertia (cal cm^{-2} K^{-1} $s^{-1/2}$)	Surface heat capacity per unit volume (J m^{-3} s^{-1})
Urban – commercial/industrial/trans.	12.9	11.9	94	200	0.029	18.7×10^5
Irrigated crop/pasture	18	50	92	15	0.04	25.0×10^5
Range/grassland	19	15	92	12	0.03	20.8×10^5
Deciduous forest	16	30	93	50	0.04	25.0×10^5
Coniferous forest	12	30	95	50	0.04	29.2×10^5
Mixed forest	13	30	94	50	0.04	41.8×10^5
Water	8	100	98	0.01	0.06	9.0×10^{25}
Marsh/wet land	14	50	95	20	0.06	29.2×10^5
Crop/grass mosaic	18	25	92	14	0.04	25.0×10^5
Mixed dry/irrigated crop/pasture	18	25	92	15	0.04	25.0×10^5
Crop/wood mosaic	16	35	93	20	0.04	25.0×10^5
Urban – low-density residential	14.5	16.8	93	60	0.032	20.6×10^5
Urban – high-density residential	11.8	12.9	94	100	0.03	18.9×10^5

Table 2. Average percent cover of trees (deciduous), grass, and impervious surfaces in each of the three urban landuse categories, for the base, maximum, and realistic MM5 simulations.

Landuse category	Base tree/grass/impervious	Maximum tree/grass/impervious	Realistic tree/grass/impervious
Urban – commercial/industrial/transportation	14% / 34% / 52%	48% / 0% / 52%	24% / 24% / 52%
Urban – low-density residential	33% / 35% / 32%	68% / 0% / 32%	43% / 25% / 32%
Urban – high-density residential	25% / 16% / 59%	41% / 0% / 59%	35% / 6% / 59%

Table 3. Base case biogenic emissions (moles) on July 15, 1995 in the NYC subdomain, and percent change in the sensitivity case scenarios.

Species	Base case emissions (moles)	Percent change, maximum case	Percent change, realistic case
NO	88,995.8	-8.0%	-2.2%
PAR	6.46153×10^6	+2.3%	+1.1%
OLE	429,661	+2.5%	+1.1%
ALD2	505,622	+4.2%	+1.7%
ISOP	7.30029×10^6	+0.1%	-0.8%

Table 4. Anthropogenic (motor vehicle + area) and base case biogenic emissions (moles) for selected compounds on July 15, 1995 in the NYC subdomain.

Species	Biogenic emissions (moles)	Anthropogenic emissions (moles)
NO	88,995.8	8.6158×10^6
PAR	6.46153×10^6	3.33545×10^7
OLE	429,661	1.01593×10^6
ALD2	505,622	621,484
ISOP	7.30029×10^6	17,388.5

Figures

Figure 1.

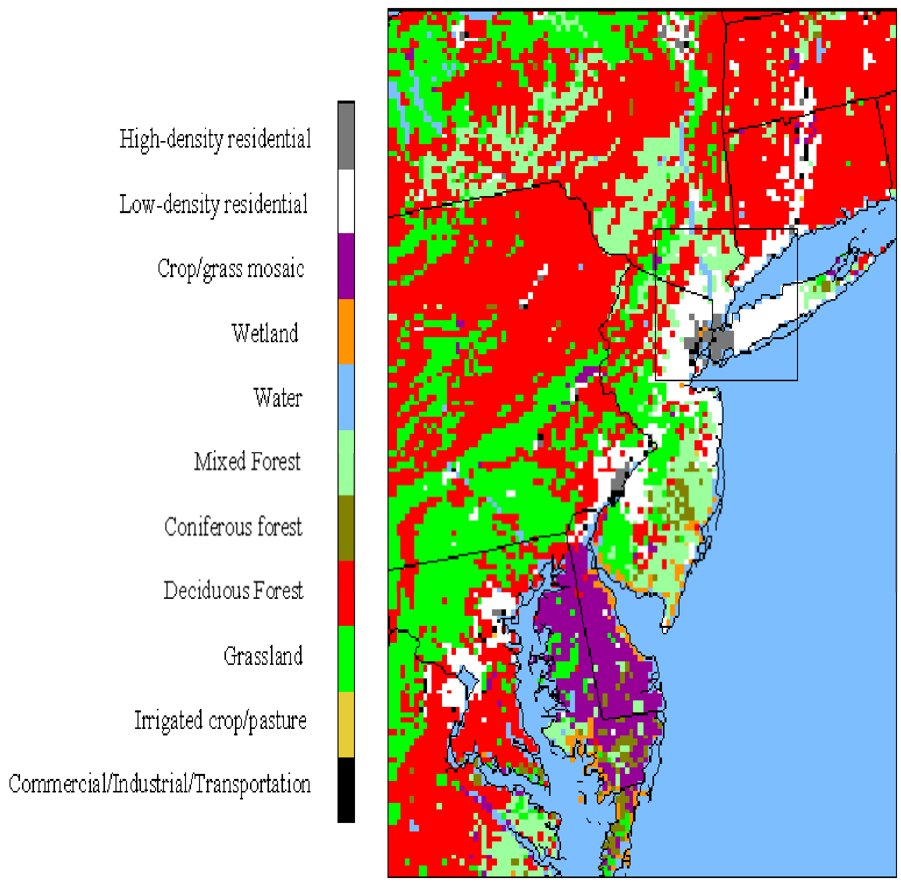

Figure 1. The 4-km modeling domain and land use/land cover. The box denotes the New York analysis subdomain.

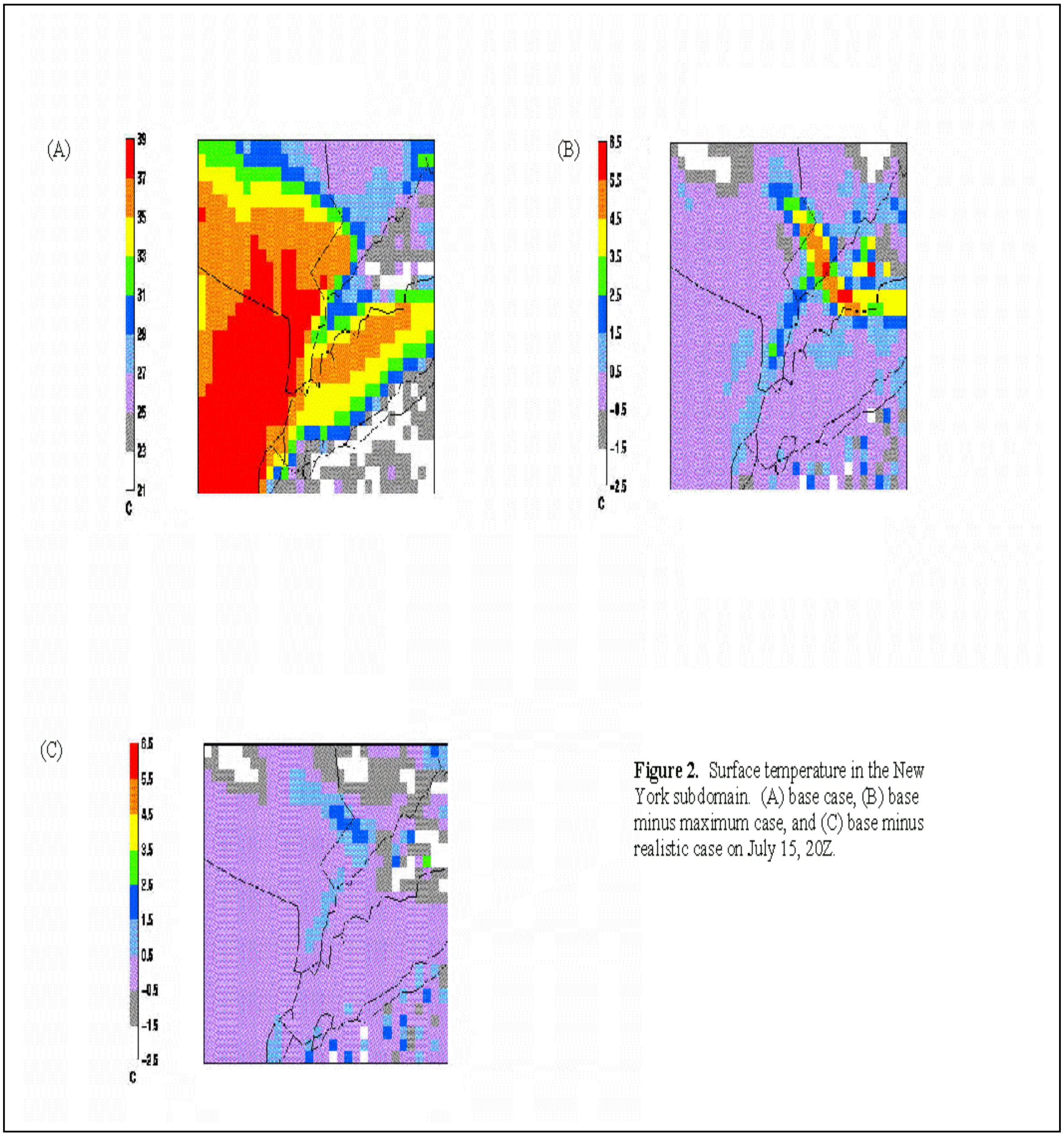

Figure 2. Surface temperature in the New York subdomain. (A) base case, (B) base minus maximum case, and (C) base minus maximum case on July 15, 20Z.

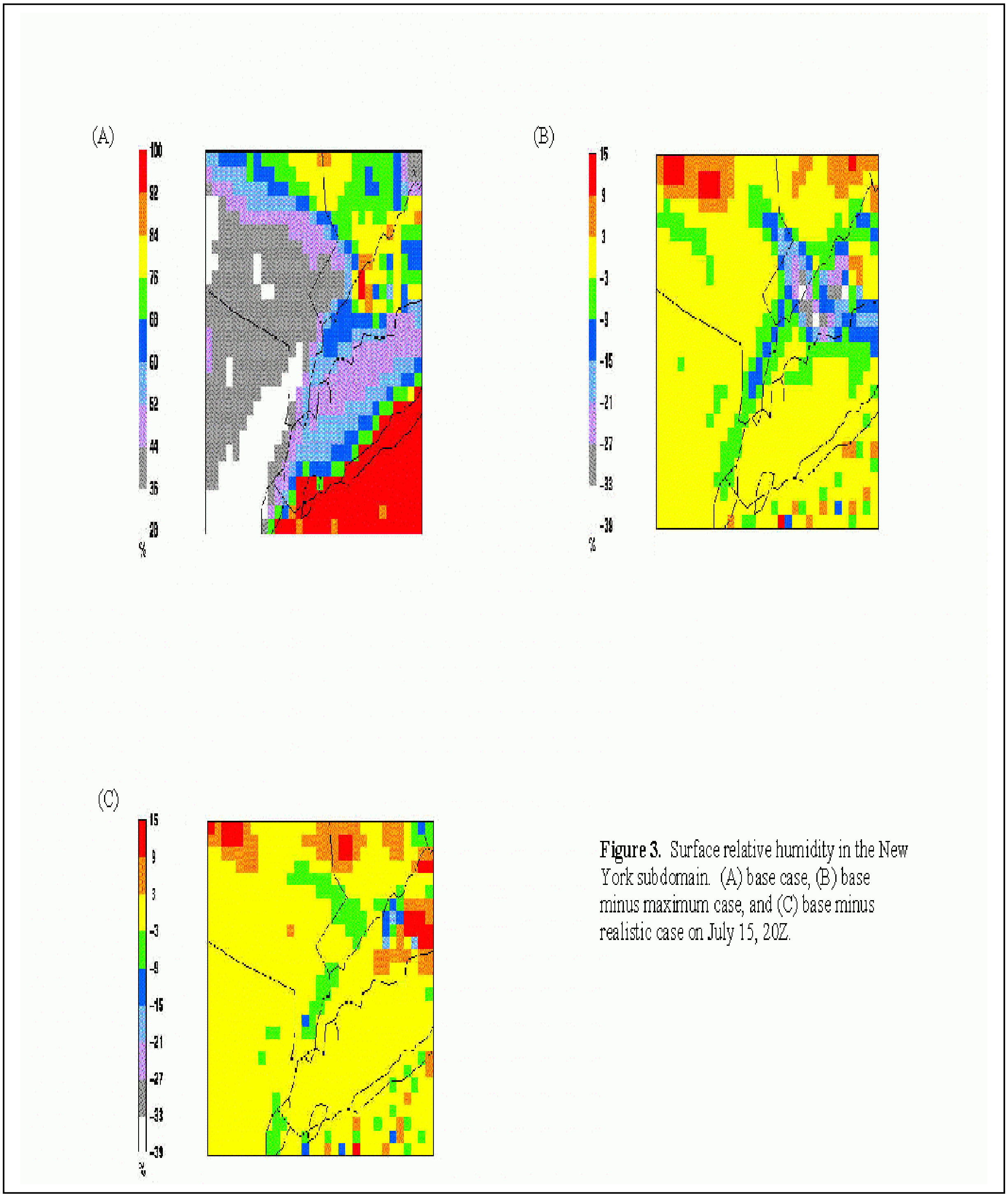

Figure 3. Surface relative humidity in the New York subdomain. (A) base case, (B) base minus maximum case, and (C) base minus maximum case on July 15, 20Z.

Figure 4. Time series of surface meteorological fields at Manhattan: (A) temperature, (B) relative humidity, (C) wind speed, (D) wind direction, and (E) diagnosed PBL height.