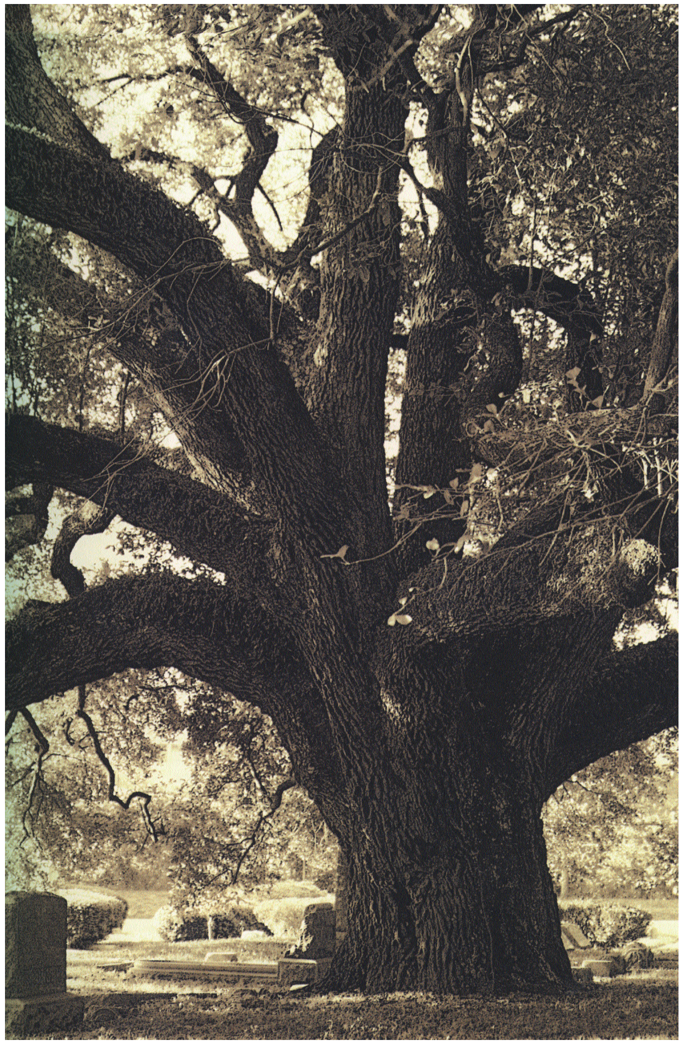

TREES & OUR AIR

The Role of Trees and Other Vegetation in Houston-Area Air Pollution

Galveston-Houston Association for Smog Prevention

Galveston-Houston Association for Smog Prevention (GHASP)

2476 Bolsover, Box 126

Houston, Texas 77005

713.528.3779

FAX 713.528.4042

email: ghasp@neosoft.com

www: http://www.neosoft.com/~ghasp

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The cover photograph is from *The Harris County Tree Registry*, 2nd edition (a project of The Park People). The "Century Oak" stands at the far south end of Glenwood Cemetery in Houston, Texas.

Acknowledgments

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Trees & Our Air attempts to summarize current knowledge about the role of trees and other vegetation in contributing to and reducing air pollution. It is by no means the last word on the subject. The role of trees and vegetation in air pollution, climate, and human health is an area of active research. We look forward to publishing an updated report as more information becomes available.

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Introduction

Ground-level ozone pollution in the Houston region regularly exceeds the standards established by the United States Environmental Protection Agency (EPA), resulting in millions of dollars of health care costs, as well as significant property, crop and plant damage.[61, 66] The Houston metropolitan area has the second worst ozone pollution problem in the country, second only to the Los Angeles area, despite the fact that the population of this region is less than one-third that of Los Angeles and the fact that Houston is not rimmed by mountains and only rarely has the kind of temperature inversions that trap pollutants over L.A.

Air in the Houston area has become somewhat cleaner since passage of the 1970 federal and the 1971 Texas Clean Air Acts, but it is not getting cleaner fast enough. Indeed, the rate of improvement lags well behind that observed in many urban areas. Numerous federal, state and local leaders who have reviewed the data predict that, unless an aggressive, multifaceted effort to reduce area pollution is mounted here, the Houston area may soon have the worst ground-level ozone problem in the nation.

This dismal prediction prompts us to take a closer look at the role that trees and other vegetation play in determining regional air quality. As a community, we need a better understanding not only of how and to what degree emissions from our trees and other vegetation contribute to the formation of ground-level ozone, but also of the many direct and indirect ways in which trees reduce air pollution and improve the quality of urban life.

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The idea that trees pollute the air first surfaced during the early 1980s, when atmospheric chemists began measuring emissions from trees. Unfortunately, this information was widely distorted and misused, to the extent that some erroneously argued that trees are a large part of the air pollution problem.

Trees and plants, like all living things, emit certain substances as by-products of their metabolism. These biogenic emissions include the oxygen we breathe and the various chemical compounds that give woods and fields and flowering shrubs their fresh and distinctive odors. In the presence of significant amounts of man-made pollution, some of the many thousands of substances that trees and plants emit become participants in the formation of ground-level ozone pollution.

Is it fair then to say that trees pollute? The best and most accurate answer is no. Trees do have emissions, but "pollution" and "emission" are not synonymous terms. Embedded in the word pollution is the concept of harm — whether to health or property or ecosystems. By themselves, the chemicals emitted by plants not only do no harm but appear to play a vital role in creating healthly environments — for plants and for people.

This report has two major sections. The first concerns emissions from trees and other vegetation and their role in area air pollution. The second summarizes available information about the direct and indirect benefits of trees on urban air quality and quality of life. It is our hope, by bringing this information together, that we can foster a more balanced and informed appreciation of the region’s trees, parks, and other green spaces.

Description of Houston-Area Vegetation

The land cover in the eight-county Houston area is exceptionally diverse, including wetlands, piney forests, mixed residential areas and agricultural lands, as well as built-up areas such as downtown Houston. Knowing the type and distribution of vegetation in the area is key to reasonably estimating biogenic emissions. Several small, focused inventories of the types and amount of vegetation in specific parts of the region have been made, including one of the Houston Arboretum[144] and one of area wetlands,[142] but there exists no comprehensive inventory of vegetation in the eight-county area, such as has been created for the Chicago area.[91] Although the Texas Department of Parks and Wildlife has developed a very useful vegetation map of Texas based on LANDSAT satellite imagery and field surveys,[2, 88] and the Texas General Land Office has developed Geographic Information Systems (GIS)-based land maps of the Gulf Coast regions, these maps do not provide the spatial resolution needed for estimating biogenic emissions.

For the most recent EPA-required computer modeling of ozone formation in the area, the Texas Natural Resource Conservation Commission (TNRCC), which is responsible for the modeling, utilized United States Geological Survey (USGS) land use/land cover (LULC) maps, along with existing and new field surveys to categorize the land within the eight counties according to its vegetation. Most areas of the U.S. have created their biogenic land cover databases in a similar way, although the best data sources differ from area to area.[2, 75]

The USGS LULC data consist of digital maps that assign general land-use categories to grids within a region. For the Texas Gulf Coast area, land was assigned to one of six general categories: urban, forest, crops, range/barren, wetlands or water. Within each of these six categories, the LULC system defines more specific land-use groupings. For example, within the "Urban or Built-Up Land" category, subdivisions include residential, industrial and commercial uses (Table 1).[136]

However, because the most recent USGS maps of the region were from data collected in 1976,[8] the TNRCC also used LANDSAT Multispectral Scanner (MSS) satellite imagery to update the USGS LULC data. The LANDSAT MSS imagery employs different spectral band widths to distinguish among different types of land use. TNRCC investigators identified pixels denoting urbanization (such nonvegetated areas as freeways and buildings), and overlaid these developed areas on the USGS LULC maps to create updated land cover maps for the region (Figure 1).

The TNRCC contracted with Radian International and Valley Research Corporation (VRC) to develop vegetation

Table 1. Land use/land cover categories, plant communities, area, and biomass identified in the Texas nonattainment counties along the Gulf of Mexico, as reported in the May 1998 Attainment Demonstration Revision to the State Implementation Plan.[30]

LULC Category	Plant Community	No. of Species	Area (hectares)	Biomass Density (kg/ha)	Total Biomass (million kg)
Residential (#11)	Beaumont residential	44	26, 540	13,245	351.52
	Houston residential	47	129,549	5,780	748.70
	Corpus residential	14	0	3,335	0
Commercial and Service (#12)	Houston commercial	22	24,334	412	10.03
	Corpus commercial	14	0	3,335	0
Industrial (#13, 15)	Houston industrial	16	42,964	700	30.07
Mixed Urban or Built-up Land (#16, 17)	Houston mixed urban	41	8,280	3,335	27.62
Cropland and Pasture (#21, 24)	Corn	1	61,622	32,337	205.63
	Cotton	1	81,935	2,644	216.64
	Oats	1	13,926	1,413	19.68
	Pasture	NA	525,919	952	500.68
	Peanuts	1	9,372	3,535	33.13
	Rice	1	256,875	1,572	403.81
	Sorghum	1	80,172	3,337	267.53
	Soybeans	1	58,657	1,744	102.30
	Watermelon	1	497	3,099	1.54
	Wheat	1	6,225	1,572	9.79
Orchards (#22)	Peach	1	87	4,068	0.35
	Pecan	1	836	2,825	2.36
Herbaceous Rangeland (#31)	Pasture	NA	13,818	952	13.15
Shrub and Brush Rangeland (#32)	Mesquite-dominated range	8	0	4,203	0
	Oak-dominated range	12	2,812	4,203	11.82
Mixed Rangeland (#33)	Mesquite-dom. mixed range	9	0	2,578	0
	Oak-dominated mixed range	13	6,167	2,578	15.90
Deciduous Forest (#41)	Post oak woodland	10	135,740	4,961	673.41
	Forested wetland	10	34,210	2,134	73.00
Evergreen Forest (#42)	Longleaf/slash pine	14	17,897	1,203	21.53
	Loblolly/shortleaf pine	30	128,501	10,603	1,362.50
	Live oak	9	16,400	11,101	182.06
Mixed Forest (#43)	Oak/pine	30	72,013	5,857	421.78
	Oak/gum/cypress	41	65,320	4,553	297.40
	Oak/hickory	43	72,328	4,043	292.42
	Live oak/post oak	8	67,500	5,241	353.77
Forested Wetland (#61)	Forested wetlands	10	15,703	2,134	33.51
Non-Forested Wetland (salt marsh) (#62)	Pasture	NA	191,397	952	182.21

emission factors to be used in the 1998 computer modeling.[111] As part of this process, Radian and VRC assigned plant communities to each LULC area based on field studies and consultations with Texas foresters. Plant communities were named according to the dominant species in each community, but a plant community might contain many plant species. Residential areas have the greatest number of plant species due to the introduction of foreign species. In Houston, for example, 47 species were identified in the residential plant community.[130] The data in Table 1 encompass the eleven Gulf Coast counties, including the eight Houston-area counties that do not meet federal standards for air quality.*

Because of uncertainties surrounding the land use and emission data employed in the most recent computer modeling, the TNRCC has recently contracted with ENVIRON International Corporation, the National Center for Atmospheric Research (NCAR), Rice University, and the University of Texas at Austin to prepare new maps for the Dallas-Fort Worth and Houston areas. The Dallas-Fort Worth maps have been completed,[2] but maps for the Houston area will not be available until approximately March 1999.[3] These maps will have considerably higher spatial resolution, and more species detail than the maps currently being used.

*Much of the modeling looked at the coastal counties together because of the proximity of these areas and because of a major 1993 study, the Coastal Oxidant Assessment for Southeast Texas (COAST) study, that collected detailed air pollution and meterological data throughout the coastal area.

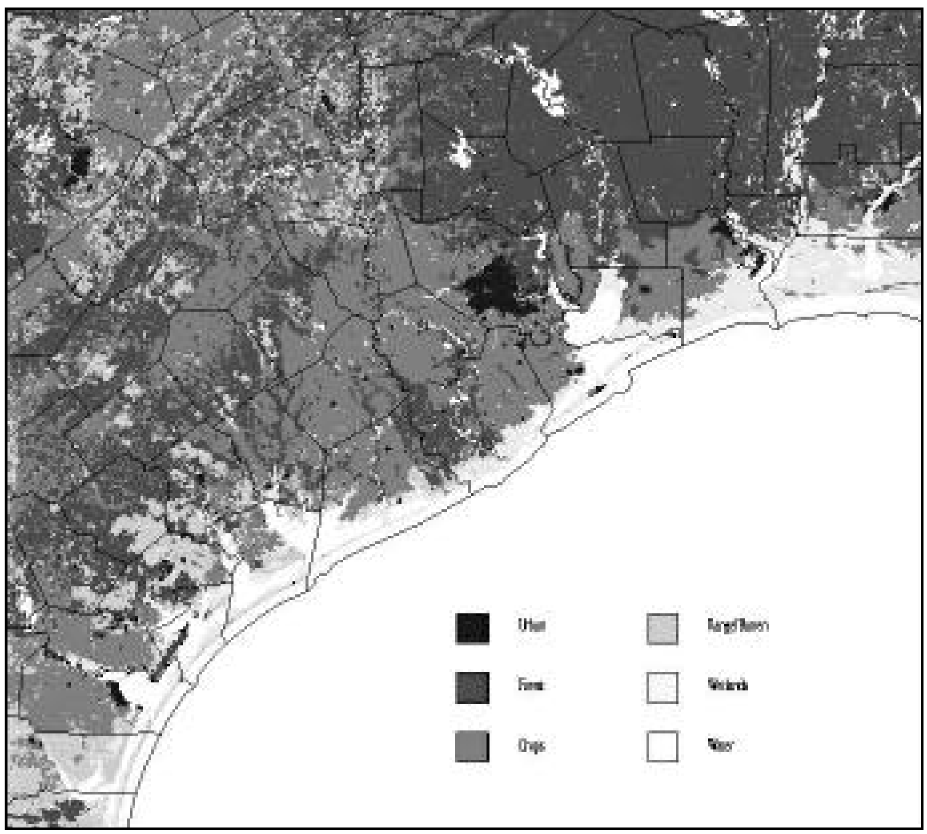

Figure 1. Updated land use/land cover (LULC) map of the Gulf coast area, as reported in the May 1998 Attainment Demonstration Revision to the State Implementation Plan, defines the vegetation distribution for the Houston-Galveston area.[130]

How Trees Contribute to Ground-level Ozone Pollution

Plant emissions are vital in the processes through which plants interact with and help to replenish the earth. Over the course of some four billion years, life has evolved in such a way that each living component of the earth's biosphere — microbes, plants and animals — exists in a complex interdependence. Soil microbes in the root zone (the rhizosphere) of plants break down organic and some inorganic substances into forms that can be used as food. Plants combine this food with water and carbon dioxide to create oxygen. Animals, including humans, combine oxygen and food coming directly or indirectly from plants to create energy and carbon dioxide.[146] To the extent that these processes remain in equilibrium, the living biosphere is self-sustaining.

Plants manufacture and emit into the air a variety of substances called phytochemicals, many of which are reactive volatile organic compounds (VOCs) — that is, they evaporate easily into the air and react readily with other molecules. Phytochemicals are produced in and released by the leaves of a plant, as well as being secreted by the roots. These chemicals help create a microenvironment for the plant that is conducive to its survival. Some of these chemicals are responsible for the distinctive smell of a pine or eucalyptus forest, or of a vitex when it is pruned. Other VOCs, such as isoprene, have little or no aroma.

In addition, microbes in the soil release small amounts of nitrogen oxides (NO_x) as they break down nitrogen-containing substances, and plants emit various pollen and spores which are necessary for reproduction.

Ground-Level Ozone Pollution

The eight-county Houston-Galveston metropolitan area experiences frequent high levels of ground-level ozone pollution during the ozone season (March through October). In 1997, Houston-area monitors, measured the highest one-hour ozone level (0.234 parts per million) in the United States, Canada or Western Europe (Figure 2); exceeded 0.20 ppm on three days; and exceeded the federal EPA one-hour standard (0.12 ppm) on 50 days (Figure 3).[15] In 1998, area monitors measured a maximum ozone reading of 0.234 ppm; 41 exceedances of the one-hour standard; and five days over 0.20 ppm.[44] During 1998, Los Angeles experienced a maximum of 0.24 ppm; 68 days above the federal one-hour ozone standard; and 12 days over 0.20 ppm (Figures 2, 3).[89]

Ground-level ozone pollution is produced by a series of complex chemical reactions primarily involving VOCs, NO_x and sunlight.[43] Because VOCs and NO_x occur at considerably higher levels in urban areas, and because urban areas experience higher summer temperatures than rural areas, the highest and most persistent levels of ground-level ozone pollution are found in urban areas. Although low levels of ozone are created naturally from biogenic VOCs and biogenic NO_X, from lightning, and from downward incursions of tropospheric ozone, ambient levels in the total absence of anthropogenic (man-made) pollution are thought to be generally less than 0.02 ppm,[149] largely because of the lack of NO_X. These low levels of naturally occurring ozone are probably beneficial, possibly important for biosystem purification.

However, chemically fertilized agricultural land, rurally located power plants or industry, airplanes, agricultural or forest fires, and transport from urban areas often introduce considerable

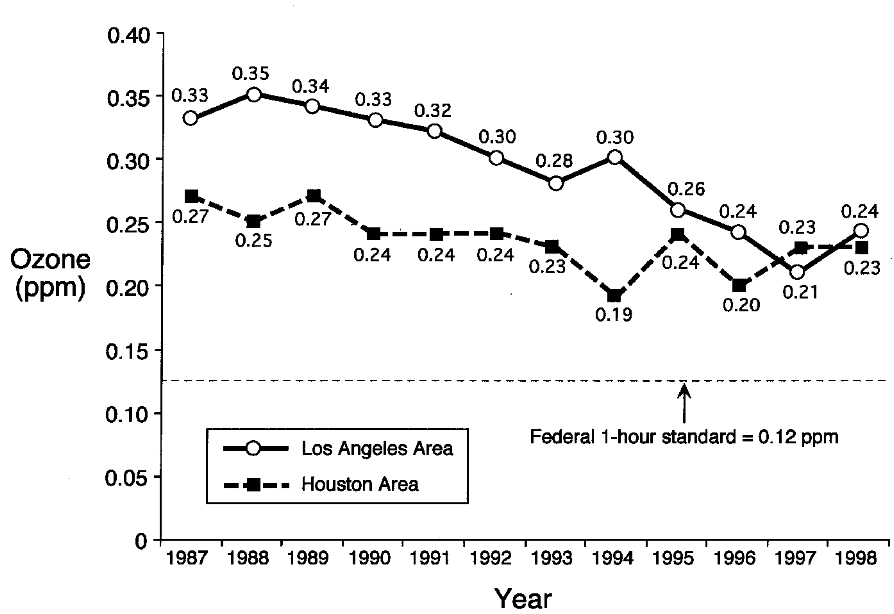

Figure 2. Maximum ozone levels recorded in the Houston-Galveston region, and in the Los Angeles area, between 1987 and 1998.

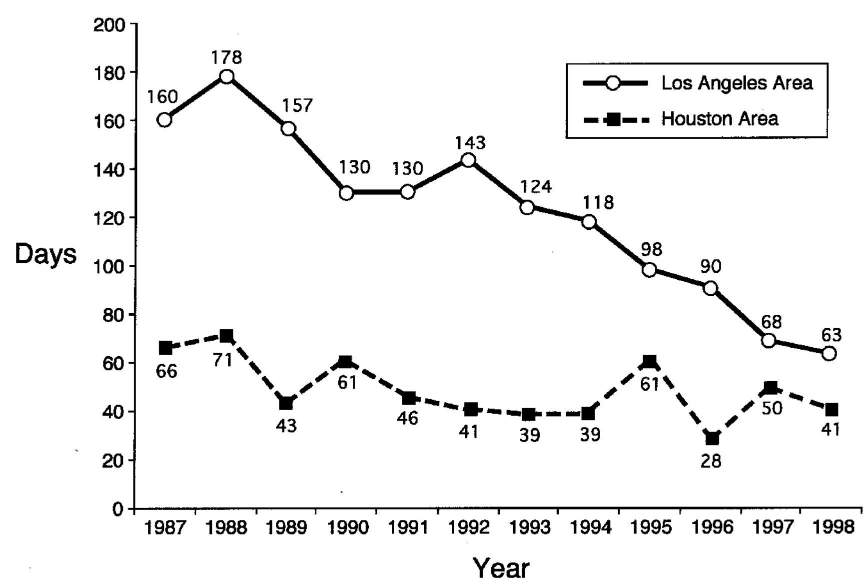

Figure 3. The number of days on which ozone exceeded the federal stan dard at one or more monitors in the Houston-Galveston region, and in the Los Angeles area, between 1987 and 1998.[39]

NO_x into rural ecosystems, leading to elevated ozone levels in the countryside. Indeed, background ozone levels in rural areas are now three to four times what they were at the end of the last century.[52] The Ozone Transport Assessment Group has analyzed ozone readings from rural sites across the U.S. and has found that these areas generally have average daily maximum ozone readings of between 0.035 and 0.040 ppm.[56] Eight-hour ozone levels in some of our national parks, however, are in the 0.06 ppm range several times each year, and at least seven of the national parks, based on 1994-96 data, will not meet the new eight-hour ozone standard of 0.08 ppm.[70]

Depending upon whether there are high levels of NO_x or VOCs in an area, ozone formation is said to be NO_X-limited or VOC-limited.

Depending upon whether there are high levels of NO_x or VOCs in an area, ozone formation is said to be NO_x-limited or VOC-limited. That is to say, if the VOC levels are high, which is often the case in wooded rural areas, then the amount of available NO_x will determine how much ozone will be formed. Conversely, if NO_x levels are especially high, as is the case in many urban areas, then the amount of available VOCs will determine the levels of ozone formed. In the Houston area, efforts to reduce ozone smog first focused on reducing VOCs. More recent modeling has indicated that an emphasis on NO_x reduction is now needed and that a 65 to 85% reduction in NO_x will be necessary for the region to attain the federal one-hour ozone standard.[130]

Volatile Organic Compounds

According to the most current computer models (discussed later in more detail), the TNRCC estimates that 65% of the VOCs in the Houston region are attributable to trees and other vegetation. VOCs are produced by all plants, although the kinds and amounts vary significantly among species, and according to the time of day, the season, and whether the plant is responding to any of such various stresses as drought or anthropogenic air pollution.

The VOCs produced by trees and other vegetation are primarily the result of photosynthesis (plant metabolism).[83] In addition to primary metabolism, in which carbon dioxide and water are converted, in the presence of sunlight, into oxygen, carbohydrate, and transpired water, many metabolic pathways lead to the formation of phytochemicals, the so-called secondary products. These secondary metabolic compounds emitted by plants appear to serve a number of purposes for the plants themselves, including attracting the appropriate pollinating insects, making the plant unsavory for noxious pests, protecting the plant from infection, and helping the plant cope with heat and ultraviolet radiation.

Societies throughout the world use the nearly endless array of plant secondary metabolic products in preparing medicines, cosmetics, and other products. Some familiar examples include penicillin from bread mold; aspirin from willow bark; the anticancer agent taxol from the Pacific yew tree; digitalis, a heart stimulant, from the leaves of the purple foxglove; solvents such as turpentine; and various spices, dyes, and perfumes. Food typically gets its taste from the presence of secondary metabolic products.

Biogenic VOCs of special interest are the terpenes. Terpenes are a rather large and heterogeneous group of substances. The simplest terpene is isoprene (2-methyl-1,3-butadiene).[83] Isoprene is a basic C5 carbon compound that is directly emitted into the air, as well as being utilized by plants to make larger structures, including other terpenes such as C10s (monoterpenes), C15s (sesquiterpenes), C20s (diterpenes), C30s (triterpenes), and C40s (carotenoids or tetraterpenes like β–carotene).[83] Each of these structures exists in many forms. Indeed, approximately 1,000 monoterpenes, 1,000 sesquiterpenes, 1,000 diterpenes, 300 triterpenes, 600 carotenoids, and 1,000 steroids have been identified.

The most volatile and reactive of the terpenes are isoprene and the monoterpenes, and these are of most concern relative to ozone formation. Isoprene is the largest component of biogenic VOC emissions in most areas,[51] including Houston.*

Because isoprene is produced during photosynthesis, naturally occurring isoprene emissions peak during the afternoon and decrease to almost nothing during the night (Figure 4). Two sharp decreases in measured isoprene levels generally occur during the day: one midmorning and the other during the peak sunlight hours. The first is thought to be the result of isoprene reacting with NO_x from morning commuters; the second is thought to relate to the closure of the stomata (pores) on the leaf surface to conserve moisture during the hottest part of the day. Monoterpenes are usually stored in leaves and other structures and are therefore emitted continuously but at fairly low levels, although a few trees may emit monoterpenes

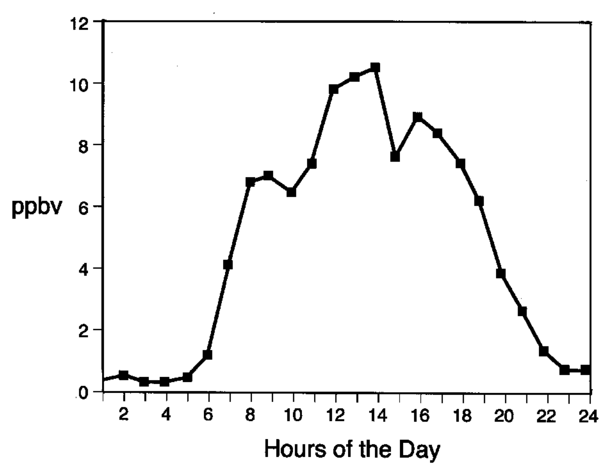

Figure 4. Typical ambient biogenic isoprene emissions measured over a 24-hour period, expressed as parts per billion by volume.[99]

*Levels of biogenic iosprene and two monoterpenes (α-pinene and β-pinene) have been measured in the Houston area at two locations: one near the Galleria and one along Clinton Drive near the Houston Ship Channel. Because of technical problems involving atmospheric moisture, the monoterpene data were not considered reliable; however, the isoprene data were considered to be valid.[40]

in a manner similar to isoprene.[20]

The toxicity of isoprene and other biogenic VOCs is thought to be low, whereas many man-made VOCs are demonstrably toxic to plants and animals.[120] Man-made VOCs include more than 75,000 different substances, most of which do not exist naturally. Little is known about the health effects of long-term exposure to the majority of these chemicals. In many instances, manufactured chemicals are similar to naturally occurring chemicals but have been altered so that they are not easily broken down by natural processes (as is the case with many plastics) or so that they are more toxic than their naturally occurring counterparts (as is the case with many herbicides and pesticides). A number of the VOCs implicated in ozone formation, such as formaldehyde and toluene, are listed among the EPA's 188 hazardous air pollutants (HAPs). The HAPs have been singled out for special emissions' reporting and control under the 1990 Clean Air Act because each is known to cause cancer, developmental disorders, endocrine disease, or other serious illness. There is no evidence that biogenic VOC emissions at the concentrations measured even in heavily forested areas are toxic.

The relative toxicity of biogenic versus man-made VOCs is important to keep in mind. Because recent computer modeling suggests that our focus for lowering ozone levels should now be on NO_x, many industry and government leaders have shifted their attention away from reducing anthropogenic VOC emissions. In terms of human and ecological health, this may be a serious mistake. Although a number of other countries including Mexico, Canada, and most of Europe have established health-based ambient standards for anthropogenic VOCs, the U.S. has not yet done so.[149]

Nitrogen Oxides

The presence alone of volatile organic compounds does not lead to ozone formation. In order for ground-level ozone to form, NO_x must be present. Small amounts of nitrogen-containing compounds are released into the air by the action of soil microbes, and by lightning, naturally occurring forest and grass fires, and volcanic eruptions. Soil is generally considered to be a negligible source of naturally occurring NO_x, contributing less than 3% to the total NO_x involved in ozone production, and usually less. Significant amounts of NO_x, however, may be produced in rural areas by the intentional burning of forests and grasslands for agriculture, and by the use of high-nitrogen chemical fertilizers.[31, 60, 82]

In the COAST study, Radian estimated that soil fertilized for growing corn emitted ten times as much NO_x as did natural grasslands, and that soil fertilized for cotton emitted 1,300 times more NO_x than did wetlands (Table 2).[111] In rural areas with significant biogenic VOCs, this agricultural NO_x may be a major factor in the increased levels of ground-level ozone measured. In the TNRCC's 1998 revision to the 1993 State

Table 2. NO_x emissions from different soils.[91]

Land Use Type	NO Emission Factor (ng N/m²/sec)	Fertilization Rate (kgNha⁻¹)
Natural Areas		
Grasslands	0.9	–
Forests	0.07	–
Wetlands	0.003	–
Agricultural Areas		
Corn	9	121 ± SD 13
Cotton	4	58 ± SD 5
Wheat	3	40 ± SD 9
Soybeans	0.2	3 ± SD 1

ng N/m^2/sec = nitrogen oxide emissions in nanograms of nitrogen per square meter per second; $kgNha^{-1}$ = kilograms of nitrogen per 1/10 of a hectare (one hectare = 2.47 acres); SD = standard deviation

regularly revised as new information becomes available. Part of this process involves using computer modeling to demonstrate how ozone is formed in the area and what control measures would be most effective in reducing the ozone levels.

In general, different methods are used to determine the contribution of each of the five major VOC and NO_x emission sources: (1) point sources (large industrial sources), (2) area sources (numerous smaller sources, such as gasoline stations, restaurants, paint shops and lawn care equipment); (3) on-road mobile sources (cars, buses, and trucks used for mobility), (4) off-road mobile sources (such as construction equipment, airplanes, and trains), and (5) biogenic sources (trees and other vegetation).

Figures 5 and 6 show the percentage contributions of VOCs and NO_x for various source categories in the Houston region and, for comparison, in the Dallas-Fort Worth region. Note that the VOC and NO_x emissions in the Houston area are approximately three times those in the Dallas area, despite the two regions having roughly the same population. This is due, for the most part, to the Houston area's large petrochemical industrial base, and to the amount of electricity used for air-conditioning and industrial generators. Houston is the world's most air-conditioned city.

Implementation Plan, discussed below, these agriculture-related sources were termed biogenic, suggesting that they naturally occurred. In more recent literature produced by the TNRCC, these NO_x sources have been more appropriately designated as agricultural NO_x.[98]

Overwhelmingly, however, NO_x is a man-made pollutant, produced by cars, trucks, power companies, industry, gasoline-powered lawn equipment, fireplaces, gas furnaces, gas stoves — by all combustion processes.

Computer Modeling of Ground-Level Ozone Pollution

Driven by the requirement to reduce ozone to safer levels, a federally mandated State Implementation Plan (SIP) has been developed by the TNRCC that defines how the Houston area might best reduce its ozone pollution and reach attainment of the one-hour federal standard for ozone by 2007. The SIP is

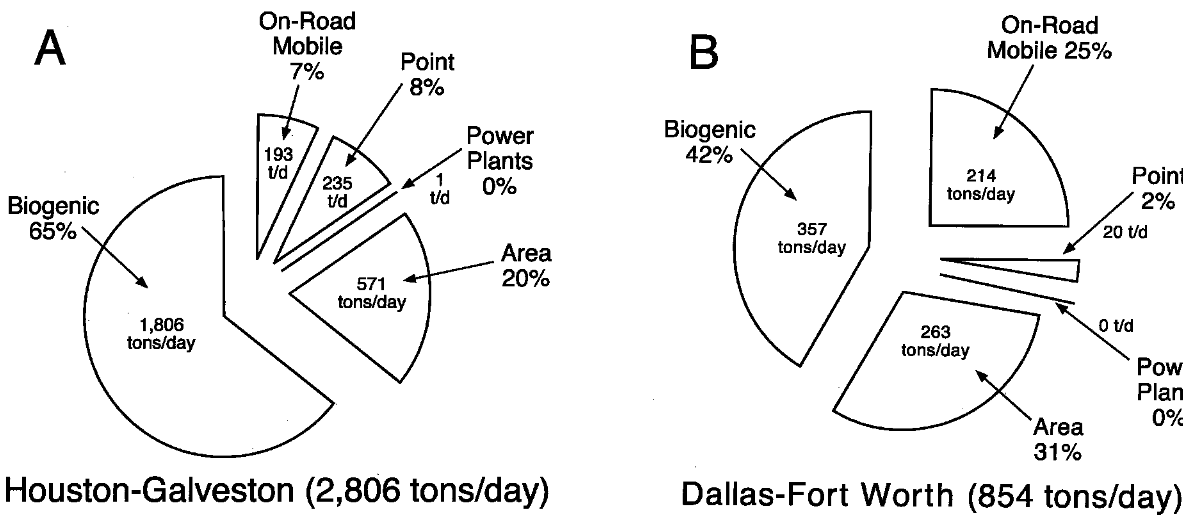

Figure 5. A. Sources of VOC emissions for the Houston-Galveston ozone nonattainment area.[98] B. Sources of VOC emissions for the Dallas-Fort Worth ozone nonattainment area.[98] In this classification of VOC sources, off-road mobile sources are included under area sources, and power plants (a point source) are listed separately

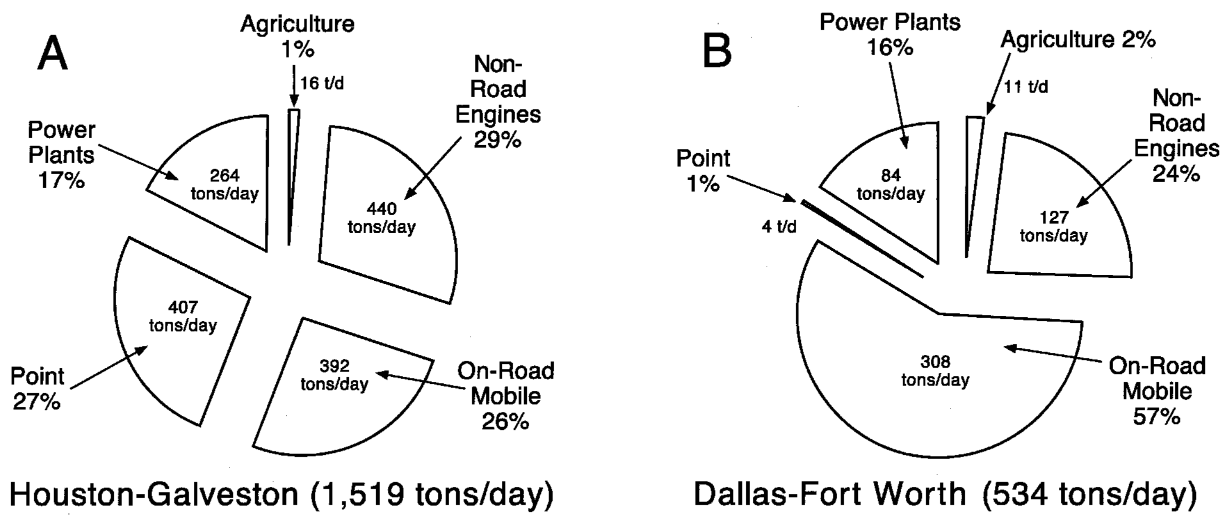

Figure 6. A. Sources of NO_x emissions for the Houston-Galveston ozone nonattainment area.[98] B. Sources of NO_x emissions for the Dallas-Fort Worth ozone nonattainment area.[98] In this classification of NO_x sources, power plants (a point source) and non-road engines (usually included under area and off-road mobile sources) are listed separately

The TNRCC estimates, based on its computer modeling, that 65% of the Houston area's VOCs are biogenic (Figure 5A), and that biogenic NO_x emissions are primarily agricultural (i.e., from chemical fertilizers), accounting for approximately 1% of the total NO_x in the Houston area (Figure 6A). Different urban areas have different vegetation profiles and meteorology, and therefore biogenics make varying contributions to the total VOCs in different regions of the country. For example, in the L.A. area biogenic VOCs only account for 10% of total VOCs,[16] whereas in Atlanta computer models show that approximately 80% of its VOCs are biogenic in origin.[54] In the Dallas area, 42% of the VOCs are biogenic (Figure 5B).[98]

Until recently the TNRCC used the EPA-approved Urban Airshed Model version V (UAM-V) to model ozone formation for the Houston region. More recently the agency has switched to another EPA-approved computer model, the Comprehensive Air quality Model with extensions (CAMx), developed by ENVIRON International.[39] In Europe, several other air quality computer models, including EMEP, EURAD, LOTOS and REM3, are being used.[57] These sophisticated computer programs assimilate information about VOC and NO_x emissions from various sources, and then combine this emission information with meteorological information and the chemical equations underlying ozone formation to create maps that estimate the creation, levels, and movement of ozone throughout a designated area. These estimated ozone levels are then compared with the actual measured ozone levels to assess how well the computer model works.*

In most of the United States a model called the Biogenic Emissions Inventory System-Version 2 (BEIS-2) is being used to estimate biogenic emissions.** However, in the Houston area the TNRCC received EPA permission to use a model called the Biogenic Model for Emissions (BIOME), which was developed by Radian International as part of the Emissions Modeling System (EMS-95) modeling package[130] and which allows the use of more area-specific data. Although the technical formulations of the two models are similar, the models produce different biogenic emissions estimates. Wilkinson and associates compared the two models for the COAST domain (Table 3).[143] For Harris County alone, they found that BEIS-2 estimated 267.1 metric tons of isoprene, whereas BIOME estimated 150.6 metric tons of isoprene, a difference of 56%. They also found that NO_x emissions were 32% higher using BIOME. Analysis of the underlying data revealed significant differences in assessments of land use, biomass density, and emission factors. For the larger coastal area, however, the estimates of the two models were relatively similar. Both models calculated considerably higher levels of biogenic VOCs than did the first version of BEIS, because the later versions incorporate more specific data from recent biogenics research (Table 3).

BIOME uses biomass, emission factors for varying species, amount of solar energy,

*For the SIP revision that was submitted to the EPA in May 1998, the TNRCC compared its modeled results with measurements made during an ozone episode that was recorded as part of the 1993 COAST study.[130]

**BEIS-3 is currently being developed and should be available sometime in 1999.[3]

Model	Isoprene (metric tons/day)	Total VOCs (metric tons/day)	Nitric Oxide (metric tons/day)
BEIS	825	1,954	78
BEIS-2	4,021	6,761	119
BIOME	3,094	7,744	76

Table 3. Estimated biogenic emissions for August 17, 1993, for the total COAST domain using three different computer models.[143]

vary significantly on different ozone episode days due to the strong effect of meteorological factors on these emissions (Table 4).

In addition, each species has a distinct VOC emissions profile. Oaks, for example, tend to be high emitters of isoprene, whereas birches tend to be relatively low emitters (Table 5). Biogenic NO_x emissions are estimated based on published studies of various species that have measured NO_x released from the soil. As noted earlier, biogenic NO_x emissions are small except where chemical fertilizers are used.

time of day, season, and temperature to estimate the amounts of biogenic VOCs released into an area (Figure 7). Table 1 lists the biomass density for different plant communities per hectare (one hectare equals 2.47 acres). The biomass, which was determined by Radian and VRC based largely on other studies, is a measure of the amount of leaves a plant species has, expressed as kilograms (1 kilogram = 2.2 pounds) of dry leaf biomass per hectare of land area. Because photosynthesis takes place in the leaves, biomass indirectly measures the metabolic capability of each species. Biogenic VOC emissions are the most variable of the emissions sources and

Areas of Uncertainty

Many uncertainties exist concerning the amount of biogenic emissions and the role they play in producing ground-level ozone in the Houston-Galveston ozone nonattainment area and elsewhere. In the Houston region and in many other regions of the country, for example, measured isoprene levels tend to be significantly lower than the modeled levels,[38, 48, 96] whereas measured anthropogenic VOC emissions, especially car and truck emissions, tend to be con-

Point VOCs (%)	Area VOCs (%)	Mobile VOCs (%)	Biogenic VOCs (%)	Total VOCs
798 (7%)	765 (7%)	434 (4%)	9,741 (83%)	11,737

Table 4. VOC emissions (tons per day) by emission source for the Houston-Galveston Beaumont-Port Arthur COAST domain on August 17, 1993, as submitted to the EPA in the May 1998 Attainment Demonstration Revision to the State Implementation Plan.[130] *In the four ozone episodes modeled, biogenic VOC emissions ranged between 4,226 and 9,741 tons per day. A different episode, September 6-11, 1993, from that shown above was ultimately selected for the attainment demonstration. The total biogenic VOC emissions estimated by BIOME in Table 3 and Table 4 are somewhat dissimilar because the domains modeled are slightly different, and because the data in Table 3 are expressed in metric tons whereas the data in Table 4 are expressed in U.S. tons.*

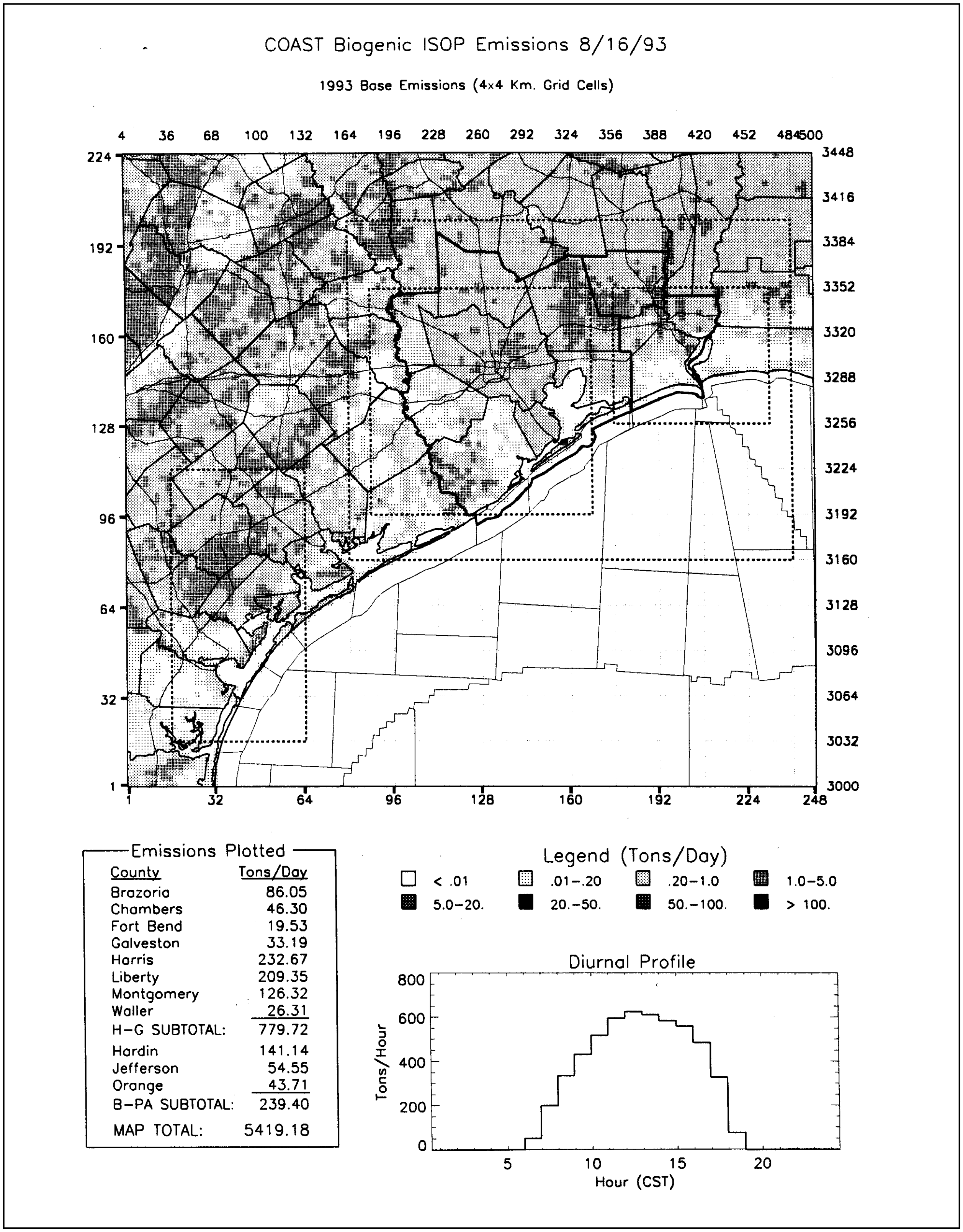

Figure 7. Modeled biogenic isoprene emissions over a 24-hour period for the COAST domain as reported in the May 1998 Attainment Demonstration Revision to the State Implementation Plan.[30]

Vegetation	Isoprene Flux (µg/m-2/h-1)	Monoterpene Flux (µg/m-2/h-1)	Other VOC Flux (µg/m-2/h-1)	NO Flux (µg/m-2/h-1)
American Elm	42.5	42.5	693.7	4.5
BEIS Urban Forest	1,988.7	663.7	920.0	4.5
Birch	42.5	85.0	693.7	4.5
Buckeye	42.5	42.5	693.7	4.5
Chinese Tallow	42.5	42.5	693.7	4.5
Corn	0.5	0	0	577.6
Cotton	7.6	19.0	11.4	256.7
Cypress	42.5	1,275.0	693.7	4.5
Dogwood	42.5	680.0	693.7	4.5
Eucalyptus	29,750.0	1,275.0	693.7	4.5
Grass	56.4	140.5	84.3	57.8
Holly	42.5	85.0	693.7	4.5
Maple	42.5	680.0	693.7	4.5
Mesquite	42.5	42.5	693.7	4.5
Oak	29,750.0	85.0	693.7	4.5
Peanuts	102.0	255.0	153.0	12.8
Pine	79.3	2,380.0	1,295.0	4.5
Redbud	42.5	42.5	693.7	4.5
Rice	102.0	255.0	153.0	0.2
Saw Palmetto	14,875.0	42.5	693.7	4.5
Sorghum	7.8	19.5	11.7	577.6
Sweet Gum	29,750.0	1,275.0	693.7	4.5
W Red Cedar	170.0	1,020.0	2,775.0	4.5
Water	0	0	0	0
Wetland Forest	3,820.0	923.0	1,232.0	0.2

Table 5. BEIS-2 emission rates for selected trees, plants, and land cover common in the Houston area.[43] The same emission rates, refined as new information becomes available, are generally used in all models.

siderably higher than modeled levels.[27] In Baton Rouge, which has a climate similar to Houston's, modeled isoprene levels were more than twice (average 8.5 ppb) that of measured isoprene levels (average 4.2 ppb).[38] To better reflect these findings, the TNRCC included an alternative ozone model in the May 1998 Attainment Demonstration SIP, one in which they used only 30% of the biogenic VOC emissions estimated by BIOME, doubled the estimated VOCs from on-road mobile sources, and increased slightly the VOCs from point and area sources, saying that this adjusted inventory correlated better with the measured ozone values than did the base inventory.[130]

As noted earlier, better characterization of area vegetation is needed, and emission rates for area trees need to be measured locally. Many of the emission rates used in the modeling were determined for species in California and the Northeast and may be inappropriate for this region. In particular the long growing season and high relative humidity of the Gulf Coast region may affect emission rates.[110] Several studies have demonstrated that similar species in different environments may have significantly different emission profiles. Brancaleoni and associates, for example, compared the emission characteristics of two oaks which are anatomically and morphologically comparable and which appear identical: the Holm oak in Southern France and the California Live oak.[20] They found that, although the Live oak emits primarily isoprene, the Holm oak emits primarily monoterpenes. In addition, the Holm oak does not store its monoterpenes as do many species but rather emits them in response to light, similar to isoprene. As the authors note, the discovery that an oak species emits primarily monoterpenes spotlights the gaps in our knowledge about emissions from plants, interspecies variability, and the influence of differing environments.

In addition, the BIOME and BEIS-2 computer models do not or only partially address a number of effects that may be important. For example, leaf stomata characteristically close during the hottest part of the day, reducing isoprene emissions considerably during the part of the day when ozone levels are typically highest (Figure 4). Although both models reduce isoprene emissions at higher temperatures (above approximately 100 ^{o}F), this phenomenon is observed at considerably lower temperatures as well, and is influenced by a number of other factors, including nutrition, drought and the availability of isoprene synthase, an enzyme necessary for the synthesis of isoprene. Additional research is needed in this area.

Also, both models estimate considerably higher isoprene emissions in the south, due to higher temperatures and greater solar radiation. Yet in one July 1994 episode in which isoprene levels in Atlanta and the Northeast were compared, the levels were approximately the same.[99] Other areas of uncertainty listed by investigators include the lack of knowledge about biogenic VOCs other than isoprene and the monoterpenes, and the possibility of unnaturally high emission factors due to disruption of vegetation during the sampling process.[110]

> *The TNRCC and the EPA have noted that the biomass factor used for the built-up area within the Houston nonattainment region appears to be inordinately high.*

Isoprene concentrations also show a midmorning dip. Researchers have hypothesized that this may be due to chemical reaction with NO_x from morning commuters, but this phenomenon needs clarification. Also, BIOME uses a maximum summertime dry leaf biomass that does not account for leaf maturation or senescence and may therefore overestimate emissions.[130] Both the TNRCC and the EPA have noted that the biomass factor used for the built-up area within the Houston nonattainment region appears to be inordinately high (3X higher than in BEIS-2).[143] As mentioned earlier, the TNRCC has contracted with the University of Texas at Austin, in conjunction with NCAR, Rice University, and ENVIRON International Corporation, to develop new biomass data for the Houston area. Preliminary findings indicate that the biomass for the Houston urban area is considerably lower than that which was used for the May 1998 SIP.[3]

Another uncertainty has to do with the effect of canopy shade. A number of different mathematical formulas exist to compensate for the effect of canopy shade, which reduces the rate of photosynthesis on a tree's lower branches. In some studies, canopy effects have been shown to lower biogenic emissions by as much as 50%.[81] BIOME and BEIS-2 utilize significantly different canopy effect formulas. TNRCC investigators hypothesize that this may in part account for the differences between the results obtained using BIOME and those obtained using BEIS-2.[130] Further research is needed to more accurately understand the effect of tree canopy on biogenic emissions. This is especially important in the Houston area which has many high-emitting, large-canopy Live oaks.

Another possibility for the discrepancy between measured and modeled isoprene levels is that biogenic VOCs may not behave like man-made VOCs. Isoprene is extremely reactive, more than eight times more reactive than automobile exhaust. University of Texas professor David Allen and others have hypothesized that some biogenic VOCs may react so quickly as to remove them from participation in ozone formation, or that their reaction products may behave differently from what the models predict.[3, 77, 99] Over the summer of 1998, Allen and associates collected samples of isoprene and isoprene reaction products at ground level and, using balloons, at specific heights over various types of tree cover at sites east and west of Austin, Texas. These data are currently being analyzed, with results expected to be available sometime in 1999.[3] The study was funded by the TNRCC.

In addition, measured levels of isoprene along the Houston Ship Channel do not fall to nothing or nearly nothing at night as is characteristic of biogenic isoprene.[40] This may be due to man-made isoprene.[40] Man-made isoprene occurs as a by-product of synthetic rubber production. A large rubber manufacturer is located near the Houston Ship Channel, and it is therefore possible that some locally measured isoprene is anthropogenic. Although in theory the footprints of biogenic and man-made isoprene can be differentiated using carbon dating, in practice this is not generally feasible.[3] Also, because reporting of releases of man-made isoprene into the air is not required, little information is available concerning anthropogenic isoprene in the area. It is likely that the actual levels of biogenic isoprene are lower than those measured here, at least along the Ship Channel.*

Although the biogenics modeling done in the Houston area appears consistent with that

*Another explanation may be that, because the reactivity of isoprene falls significantly once the sun sets, there is residual isoprene that slowly dissipates during the night.[3] This, however, would not explain the difference between the Ship Channel and Galleria sites, nor the observations at other sites where measured isoprene falls to almost nothing at night.[99]

done in other areas, the TNRCC's decision to ask Radian International to supply most of the data used to estimate biogenic emissions, as well as to use a computer model developed by Radian, deserves scrutiny. Radian's primary business is providing environmental services to industry. Radian manages the Houston Regional Monitoring network, a system of industry-sponsored air monitors along the Ship Channel, and was acquired by Hartford Steam Boiler Inspection & Insurance Company and Dow Chemical Company in January 1996. Three months later the EPA issued stop-work orders on $12 million in contracts it had with Radian, noting that "no company providing services to the EPA can be allowed to hold a financial stake — or even the appearance of a financial stake — in the outcome of our policies."[102] Because Dow and other area industries are significantly affected by the results of area ozone modeling, it may be inappropriate for the State of Texas to use Radian as a primary source of information from which to make decisions about the regulated community.*

One of the more subtly troubling aspects of the computer programs that model ozone formation is that none adequately addresses the myriad of ways that vegetation, especially trees, reduce ground-level ozone pollution. Recent versions of UAM and CAMx do include mathematical models that simulate the removal of soluble gases and tiny particulates from the air through wet deposition (e.g., rain and snow), as well as by dry deposition onto the surfaces of vegetation and soil. Dry deposition attempts to take into account the solubility and reactivity of various gases, surface roughness, air turbulence, moisture, temperature, and land-use characteristics. However, considerably more effort has gone into calculating the emissions of vegetation than into calculating their pollution-removing capabilities. Indeed, although several studies suggest that trees reduce urban VOC emissions in excess of the VOCs they themselves produce,[5, 100] ozone computer models tend to treat trees much like industrial sources, with the number of trees correlating linearly with increased pollution.

Dry deposition rates have not been measured for specific trees, nor have vegetation's effects on a number of factors that affect air pollution, including erosion, temperature and rainfall, been adequately addressed. Although UAM, CAMx and other computer models are widely used to study the effect on ozone levels of reducing man-made pollution, these models are not yet capable of accurately simulating the effects of tree-planting programs on regional air quality.** The effect of area particulate levels on ozone formation is also sel-

*The BIOME model does offer a number of advantages over BEIS-2, and is being used in the new biogenics inventory being developed, by a different set of contractors, for the Houston area. The work by Radian for the 1998 SIP revision was done before the merger with Hartford Steam and Dow Chemical.

** Such analyses are, however, being done separately. Both American Forest's Urban Ecosystem Analysis (UEA), which utilizes a GIS-based software package (including CITYgreen, ArcView, ArcInfo and ArcView Special Analyst), and also QuantiTree's benefit and cost software are being used in various urban areas to calculate air pollution mitigation, stormwater runoff reduction, and other benefits of urban trees.[132]

dom included in ozone simulations, despite the fact that both UAM and CAMx have this capability and despite growing evidence suggesting that particulate pollution plays a much larger role in ozone formation than previously appreciated. As discussed in the next section, trees and soil are particularly effective in removing particulate pollution from the air. Clearly, much more rigorous work needs to be done on the pollution-reducing abilities of trees.

For a few years there was talk that reducing the number of trees in urban areas might reduce urban air pollution, but it is now broadly recognized that the benefits of trees vastly outweigh any disbenefits. Although some people have reasonably suggested that urban air might be improved by choosing low-emitting trees for large tree-planting programs,[17, 74] the usefulness of even this suggestion is unclear. Often it is the giant canopy trees, such as the oaks, that are high emitters. And yet these trees generally provide the greatest cooling and pollution-lowering effects in urban areas.

How Trees and Other Vegetation Reduce Urban Air Pollution

Trees and other vegetation directly remove many gaseous and particulate pollutants from the air, and indirectly reduce air pollution as well. In the Chicago area, the U.S. Department of Forestry calculated that a single tree with a trunk circumference of 30 inches removes 200 pounds of carbon dioxide, 1.1 pounds of ozone, and 2 pounds each of sulfur dioxide, particulates, and nitrogen dioxide every year, with the greatest removal taking place during the summer months (Figure 8).[100] In addition, plants efficiently remove many toxic chemicals, such as formaldehyde and benzene, from the air,[146] and can effectively clean the soil in their root zones of many toxic man-made chemicals.[139] Indeed, a recent study of the effects of urban tree cover in Atlanta, which currently has 27% tree cover, found that the existing cover saved area residents $15 million in pollution-control devices. Were the tree cover to be increased to the recommended 40%, an additional $7 million in air quality benefits could be realized.[6]

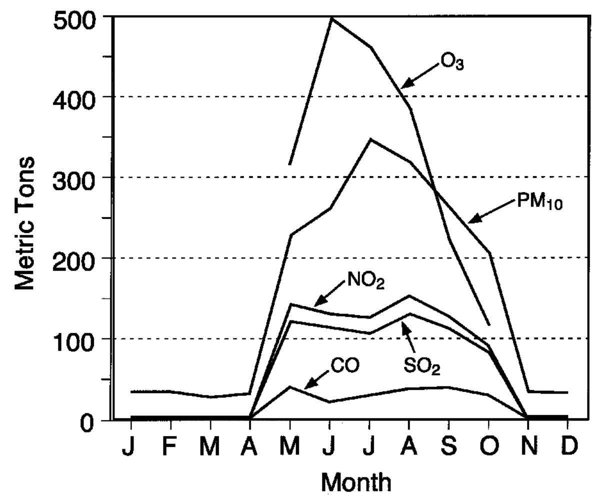

Figure 8. Air pollution reduction in the Chicago area in 1991. Particulate removal assumes 50% resuspension back to the air.[100]

Those parts of the earth's biosphere that remove pollutants from the air and store, metabolize, or transfer them are called sinks.[140] The transfer of contaminants from the air to the soil or the surfaces of vegetation is expressed as a flux (pollutant uptake) rate. Actual determinations of flux rates are extremely complex and involve consideration of atmospheric conditions (wind, turbulence, temperature, humidity), the nature of the pollutant and its concentration, sink surface conditions (geometry, presence or absence of moisture, affinity for the pollutant), and other parameters.[123]

The soil, roots, and vegetative portions (leaves, stems and bark) of urban forest ecosystems all function as sinks for atmospheric pollution. Pollutants can be moved through a plant by means of translocation, which involves two tissue systems: xylem and phloem. Xylem primarily moves minerals and water from the roots to the foliage, whereas phloem primarily moves sugars and other dissolved foods from the foliage to all non-green plant cells. By these means, chemical pollutants absorbed by the leaves can be translocated to the root areas where they can be broken down by microbes and, conversely, pollutants absorbed by the roots can be broken down and translocated to the leaves where they may be released into the atmosphere.[139]

Trees Remove Ozone and Other Gaseous Polluants

Both the soil and vegetative surfaces are active in removing gaseous pollutants, such as ozone, nitrogen dioxide, sulfur dioxide, formaldehyde, benzene, and hydrogen fluoride, from the atmosphere. Soils have considerable capacity to remove gases from the atmosphere and to incorporate and transform them in or on the soil through microbial, physical, and chemical processes. Healthy, biologically active soil is, as one might suppose, more efficient at this process than is degraded soil. More detailed information is needed, however, on (1) the capacities and rates of adsorption of various soils, (2) the residence and reaction rates, (3) the influence of a soil's physical (mineral and organic content, structure, porosity) and chemical (pH, moisture content, exchange capacity) properties, (4) the effect of climate on removal rates, and (5) the significance of soil management practices.[123]

In addition to the soil, vegetative surfaces, especially the leaves, remove gaseous pollution from the atmosphere.[123] Pollutants that are soluble in water are most easily absorbed by leaf surfaces. Hydrogen fluoride, sulfur dioxide, nitrogen dioxide, and ozone, which are soluble in water, are readily absorbed. Nitric oxide and carbon monoxide, which are insoluble, are absorbed relatively slowly or not at all. When vegetative surfaces are wet or damp, the pollutant removal rate may increase up to ten-fold. Under damp conditions, the entire plant surface — leaves, twigs, branches, and stems — is available for uptake. The high relative humidity and high annual rainfall of the Houston area facilitates pollution removal by area trees and other vegetation.

Light also plays an important role in determining the physiological activities of the leaf, including the opening and closing of the leaf's stomata, and thereby significantly influences foliar removal of air pollutants. Under conditions of adequate soil moisture, pollutant uptake by vegetation is almost constant throughout the day because the stomata are fully open. Under conditions of drought or insufficient access to moisture (as is often experienced by urban vegetation), the stomata partially close to limit moisture loss, severely reducing the uptake of gaseous pollutants. Similarly, pollutants are absorbed most efficiently by foliage near the canopy surface, where light-mediated diffusion and metabolic activity are greatest.

Studies conducted by the National Aeronautics and Space Administration (NASA) to investigate how to maintain healthy air in spacecraft have found plants to be one of the most efficient and effective mechanisms for cleaning the air of contaminants, and for supplying vital oxygen. Studies sponsored by NASA found, for example, that a Boston fern removes 20 micrograms of formaldehyde per hour and one Areca palm removes 19 micrograms of xylene and toluene per hour from the air.[146] In addition, these studies demonstrated that the VOCs released by plants suppress mold spores and bacteria found in the air and that plant-filled rooms contain 50 to 60% fewer airborne molds and bacteria than rooms without plants.[145] Although these benefits have not been investigated in urban ambient air, common sense would suggest that the benefits could be significant.

In his book *Air Pollution and Forests: Interactions between Air Contaminants and Forest Ecosystems*, William Smith writes:

> Under certain environmental conditions, especially when tree surfaces are wet and when leaves are metabolically active, medically and biologically significant reductions in ambient levels of sulfur dioxide, nitrogen dioxide, ozone, and hydrogen fluoride may be realized…as long as the atmospheric loading of the contaminant gases is not excessive.[123]

Smith goes on to say that:

> The use of forest areas as the exclusive means to reduce ambient pollution levels associated with point industrial source facilities is not practical because of the large size of wooded hectares required. …The use of greenbelts surrounding industrial or power-generating facilities, however, can certainly contribute to improved air quality and their costs can be justified in recognition of the additional, multiple-use benefits realized.[123]

Trees Remove Carbon Dioxide

Carbon dioxide (CO_2) is one of the greenhouse gases, the levels of which have increased dramatically over the last century. Increased CO_2 levels are thought to be the primary cause of global warming and are attributable almost entirely to increased fossil fuel combustion (75%) and to deforestation.[101] Although CO_2 is necessary for photosynthesis and is stored in biomass, the amount of CO_2 currently being produced greatly exceeds the ability of the earth's vegetation to process it into oxygen and to store it as carbon.

Each person in the United States generates 2.3 tons of carbon dioxide every year, almost half of which comes from driving an automobile. An acre of trees absorbs about 2.6 tons of carbon dioxide per year; a single tree stores about 13 pounds of carbon annually. An acre of trees absorbs enough carbon dioxide over a year's time to equal the amount produced by driving a car 26,000 miles.[4] The Chicago study calculated that Chicago-area trees store a total of 6.1 million tons of carbon.[101] Large trees were found to store up to 1,000 times more carbon than small trees, and the rate of storage by large trees was approximately 90 times greater than the rate of storage by small trees.

Although there is wide scientific consensus that anthropogenic CO_2 emissions must be reduced, planting and protecting trees are also effective mechanisms for reducing atmospheric CO_2. American Forests (formerly the American Forestry Association) has calculated that planting trees is the least expensive way to reduce atmospheric CO_2. However, because trees release carbon when they die and because large trees are more effective in removing CO_2 than are small trees, protecting existing trees is also critical for reducing CO_2 levels. Tree planting reduces one pound of CO_2 for about 1 cent, whereas driving more efficient cars costs about 10 cents per pound. If every American family planted just one tree, the amount of CO_2 in the atmosphere would be reduced by one billion pounds annually. This is almost 5% of the amount that human activity worldwide pumps into the atmosphere each year.[4]

> *If every American family planted just one tree, the amount of CO_2 in the atmosphere would be reduced by one billion pounds annually.*

Trees Remove Particulate Pollution

Trees and soil also help to remove particulates from the air. Increased levels of tiny (2.5 microns or smaller in diameter) particulates in the air, virtually all of which are the result of combustion — cars, lawn mowers, industrial processes —have been correlated in numerous studies with increased respiratory disease, asthma, and cardiovascular and respiratory mortality.[35, 36, 114] In the Chicago area, which has an average tree cover of 19%, trees remove up to 2,027 tons of particulates each year.[47, 100] Removal of particulates near heavily traveled roads and freeways (where particulate concentrations are highest and most toxic) has been shown to be even higher.[63] In Fort Worth, which has an average tree cover of 24%, trees removed approximately 592 tons of particulates on 1996.[131]

Although urban soils are generally less healthy and biologically active than are rural soils due to impaction, the use of pesticides, and pollution in general, urban soil nevertheless plays an active role in removing man-made particulates from the air.

Particles are transferred from the atmosphere to soil directly by dry deposition and by precipitation, and indirectly via leaf and twig fall. The evidence that soil may be the ultimate or temporary repository for toxic metals associated with these particles is substantial. Soils, particularly the clay and organic colloidal components of soil, have an especially high affinity for heavy metals.[67, 76, 80, 85, 107, 124, 126, 150, 151]

Much of the understanding of the mechanics of deposition of particles on the surfaces of leaves and other surfaces has been gleaned from studies of particles in the size range of 1-50 microns.[1, 24-26, 53, 65, 122] From these studies it is possible to say the following:

- The interception and retention of particles by plants are highly variable and are primarily dependent on (1) the size, shape, wetness, and surface texture of the particles; (2) the size, shape, wetness, and surface texture of the intercepting plant part; and (3) the microclimate surrounding the plant.
- Generally, greater leaf surface roughness increases particle capture efficiency. Surface roughness increases the turbulence of the air flow surrounding the leaf and thereby increases particle impaction. Leaf hairs and leaf veins are the principal contributors to surface roughness. Species with smooth leaves (for example, Horse chestnut and Yellow poplar) are less efficient in collecting particles than are species with rough leaves (for example, elm and hazel).
- Particle deposition (but probably not retention) is heaviest at the leaf tip and along leaf margins where air flow is more turbulent. Leaves with complex shapes and large circumference-to-area ratios collect particles most efficiently.
- Collection of atmospheric particles by leafless trees in the winter may remain quite high due to twig and shoot impaction.

Trees Cool Urban Areas

Summers in our cities are hot and getting hotter. The difference in temperature between rural and urban space on the same day can be significant. In New York City the difference is approximately 10^{o}F; in Mexico City the difference is 18^{o}F.[134] In Atlanta, temperatures at the airport and downtown have increased substantially over the last 20 years, for an urban-rural differential of 12^{o}F (Figure 9).[6] On a summer day in Houston, the urban tempera-

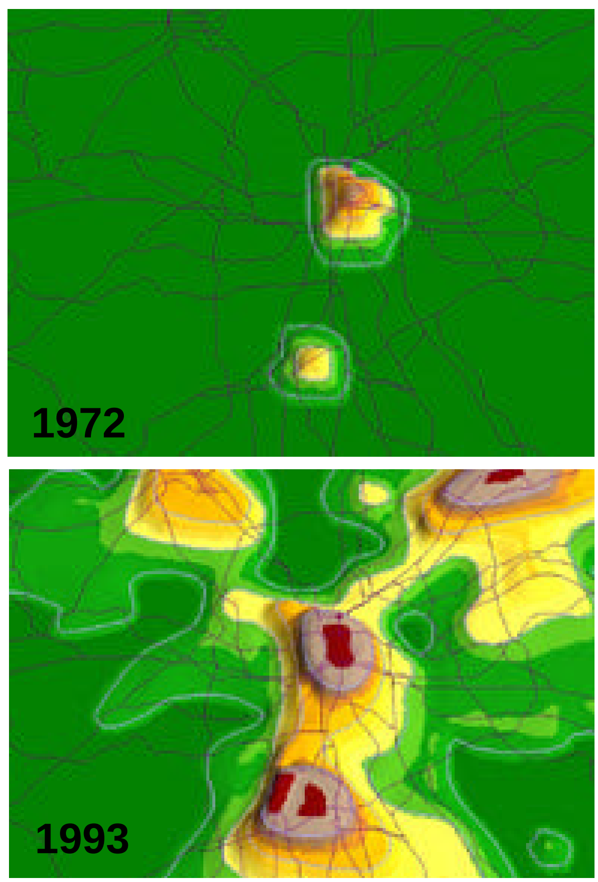

Figure 9. Atlanta in 1972 and 1993. The growing urban heat island corresponds to the replacement of trees and other vegetation with concrete, asphalt and other surfaces. The centers of the heat islands in 1993 are up to 12 degrees hotter than the surrounding countryside.

ture is approximately 8^{o}F higher than the surrounding rural temperature. This difference is expected to increase as more and more green space is lost to roads, parking lots, and buildings.

Even within a city, temperatures vary significantly, with large urban forests typically being 7^{o}F cooler than the surrounding neighborhood.[4] Dale Quattrochi, a NASA researcher, notes that the temperature of artificial surfaces can be 20^{o} to 40^{o}F higher than that of vegetated surfaces. The heat emitted by these surfaces creates a heat dome over cities.[125] The problem is exacerbated by the increasing development, pollution, and concrete that accelerate tree loss. In New York City, for example, 20% of its urban forest has been lost in the past decade.[134]

The causes of the increased temperatures in cities are well understood. Concrete, asphalt, bricks, and buildings absorb and store solar energy (heat), creating urban heat islands. These surfaces then release this heat during the night, preventing significant overnight cooling in the city. The higher heat increases the volatilization of VOCs (which is heat dependent), which then creates more pollution. The cloud of pollution lying over the city further traps heat.

Planting trees is one of the easiest and cheapest strategies for countering the urban heat island effect. Trees and other vegetation reduce temperatures in three ways: (1) trees use solar energy for photosynthesis, converting the energy into food (carbohydrate) and oxygen; (2) trees provide shade, thereby cooling surfaces; and (3) trees use evapotranspiration to cool themselves and the surrounding air. The energy savings can be significant and, increasingly, medical savings will become a major factor as each summer more and more people — especially young children and the elderly — are succumbing to urban heat.

Investigators have found that three mature shade trees planted on the southeast and southwest sides of a house can cut air-conditioning costs by up to 50%.

The shade provided by trees directly cools man-made surfaces, as well as significantly reducing air-conditioning demands in the summer.[132, 90] Investigators have found that three mature shade trees planted on the southeast and southwest sides of a house can cut air-conditioning costs by up to 50%.[4] In Fort Worth, researchers calculated that in 1996 the city's tree cover provided $61.5 million in energy savings.[131] In Washington, D.C., air conditioning of federal buildings costs taxpayers $52 million each year; in the Houston area the per building costs of cooling city and county buildings are considerably higher. A program of tree planting and albedo technology (the use of reflective surfaces) could save area taxpayers millions of dollars every year. Nationwide, it is estimated that planting trees and lightening surfaces through white-washing our buildings and roads could save up to 40 billion kilowatts of electricity each year.[4]

Evapotranspiration, the mechanism by which plants use moisture to cool the air around them, is the exact same mechanism utilized in evaporative air conditioners and can have a significant cooling effect, especially in dry hot climates. A single large tree, for example, can transpire up to 100 gallons of water a day, producing a cooling effect similar to that of five average air conditioners running for 20 hours.[4] Evapotranspiration also affects the weather. In parts of the world where large areas of tree cover have been removed, ambient temperatures have risen and summer precipitation has decreased by 10 to 20%. Planting trees can help stabilize rainfall by returning moisture to the atmosphere.

> *Nationwide, it is estimated that planting trees and lightening surfaces through white-washing our buildings and roads could save up to 40 billion kilowatts of electricity each year.*

Using vegetation and albedo technology to cool urban areas also reduces ozone and VOC pollution considerably because (1) the rate of vaporization of VOCs increases with temperature, and (2) the formation of ozone itself is heat dependent; that is, VOCs and NO_x mix in sunlight at higher temperatures to form ozone. Lower temperatures mean lower ozone levels. A study of California's South Coast Air Basin (SoCAB), which includes Los Angeles, demonstrated that exposure to ozone levels above the national standard would be reduced by up to 20% during the peak afternoon hours if widespread use of high-albedo building materials and reforestation of low vegetation urban areas were implemented.[128] The study showed that the ozone-reducing benefits of albedo and vegetation-increase strategies in the SoCAB would be comparable to converting at least 50% of the area cars operating in 1987 to zero-emission vehicles.[128]

In addition, by shading homes and offices, trees can reduce air conditioning needs, thus reducing the amount of fossil fuel burned to produce electricity for air conditioning and lowering the pollution created by power companies. In the Houston area, power generation is the largest single source of NO_x and of carbon dioxide.

Trees Reduce Noise and Light Pollution

Lack of quiet, green areas of aesthetic repose may relate to an increase in psychological and physiological stress among urban inhabitants, and possibly to increased violence. In one study, researchers compared arrest rates, by age groups, of people living in different parts of a housing project in Boston: an inner portion with normal urban noise levels, and an outer portion that that was exposed to heavy freeway noise. Researchers found the arrest rate to be higher in every age group (up to 3.3 times higher) in the noisy setting.[30] Urban parks, trees along streets, and greenbelts are highly effective as visual and noise barriers. One study found that a well-placed stand of trees can reduce urban noise by up to 15 decibels, approximately the same as a typical masonry sound barrier.[117]

Trees also reduce light pollution in locations subjected to intense lighting from street lights or other sources. Numerous studies have shown that biological clocks are disrupted by artificial lighting at inappropriate times, and that sleep disturbances can result. Lack of sufficient sleep is a growing problem in the United States.

Trees Make Oxygen

An estimated 170 billion tons of dry plant biomass are produced by photosynthesis by all plants each year. For each dry ton of biomass produced, approximately 1.4 tons of oxygen are added to the atmosphere.[146] Based on studies of astronauts, approximately 1.4 pounds of new dry plant material must be produced by photosynthesis each day to supply the oxygen needs of one adult.[146]

According to American Forests, an average-sized tree releases enough oxygen throughout one day to keep a family of four breathing. An acre of trees produces enough oxygen to meet the daily breathing requirements for 18 people.[4]

Trees Reduce Erosion, Runoff and Water Pollution

Deforestation is a primary cause of flooding. Much of the flood damage and loss of life that occurred in Honduras and other Central American countries during and following the 1998 hurricane Mitch has been directly attributed to deforestation in those countries. Trees and other vegetation reduce flooding and wind-related damage by holding soils in place, and by absorbing through their roots and canopies significant volumes of rain water. By lessening erosion and decontaminating the soil, trees and other vegetation reduce the amount of toxic particulates that are released into the air. The moisture released into the air by trees stabilizes rainfall, decreasing the episodes of drought and deluge which exacerbate flooding. By reducing stormwater flooding, trees and other vegetation reduce the amount of pollutants washed into the bayous and other waterways, many of which subsequently evaporate into the air.

A single large Live oak can consume up to 300 gallons of water each day,[45] and the canopy of a single large Live oak can intercept up to 28% of a major rain.[7] In studies conducted in Atlanta, Baltimore, Milwaukee, and Austin, tree cover produced significant dollar benefits for stormwater management. In Atlanta, for example, the city's tree cover provided $883 million in stormwater benefits. In Baltimore, Milwaukee, and Austin, trees provided $340 million, $305 million, and $122 million in stormwater benefits, respectively.[6] The benefits were calculated as one-time capital costs to build stormwater retention facilities to provide benefits equivalent to that of the trees and vegetation. Increasing urban tree cover to the recommended 40% nationwide would produce over $100 billion in additional stormwater management benefits.[6]

Trees also reduce the amount of sediment in stormwater runoff. A 1969 study in Washington, D.C., and Baltimore demonstrated that stormwater sediment from forested lands came to approximately 50 tons per square mile per year, whereas sediment from developed tree-poor areas could reach 25,000 to 50,000 tons of sediment per square mile per year.[132] Such sediment exacerbates flooding, and the cost of removing sediment is huge.

Tree roots also filter ground water, trapping nutrients and pollutants that could contaminate it. This is especially important in the Houston-Galveston region as our stormwater and bayou system drains directly into the Gulf of Mexico. Contamination of area stormwater runoff with lawn and garden pesticides and with highway pollutants is a major source of pollution in the Gulf and threatens the region's fishing industry.

Other Ways in Which Trees Enhance Urban Life

The value of urban forest and other vegetation extends well beyond air pollution reduction and includes many hard-to-quantify but significant benefits, such as beautification. But even such relatively intangible benefits may lower air pollution indirectly because, with increased pride and caring, other programs to protect and improve the area will be born, the cutting of trees will increasingly be met with protest, cleaner industry will be attracted to the area, people will be more willing to bike to work or to ride public transportation — the list goes on. The effect, as has been shown in other cities, is that a more beautiful and healthy environment spurs the desire for an even more beautiful and healthy environment, as well as a willingness to participate in its realization.

Trees Provide Aesthetic and Psychological Benefits

Trees and green space greatly enhance the visual appeal of any urban area. Tree-lined streets with pockets of flowering shrubs and flowers literally and figuratively cool the streets, encouraging civility, calm, pride, and hope within urban neighborhoods, even within those in disrepair.[30, 50, 59, 91] Several studies have suggested that loss of pride in one's surroundings may lead to a loss of pride in oneself and to a lower level of performance. In an urban setting, loss of pride has been linked to a decrease in feelings of responsibility to one's neighborhood and to its inhabitants, to increased graffiti, litter and other forms of property violence, and to feelings of urban isolation and depression.

Neighborhood parks and pockets of vegetation help instill pride, and may also lower accident rates, increase safety, and bolster psychological health. A University of Montreal study of pedestrian and bicycle accidents in Montreal among residents under age 15, for example, found that the number was not random, and that high-risk areas were characterized by an absence of parks.[68]

Trees Increase Property Values

The aesthetic and energy-saving benefits of green space and trees add considerably to the value of residential property. Some statistics suggest that landscaping can speed the sale of a home by five to six weeks and may add between 7 and 14% to a home's value.[91] In Houston, a mature well-placed healthy Live oak (60 years or older) may be appraised at up to $10,000.[45] The older Houston neighborhoods in River Oaks, the Heights, and along South and North Boulevards are valued in large part because of their tree-lined streets. A 1983 New York study demonstrated that homes with trees sold for an average of $9,500 more than homes without trees.[132]

Trees Increase the Value of the Community for Relocation

The aesthetic value of green space and trees also adds to the desirability of urban areas for personal and business relocation.[30] Cities with forested parks and green belts help to create healthier communities and are more sought after by families, individuals, and businesses as desirable environments in which to live, play, and work. Choosing a healthy place in which to raise children is also a growing consideration when families relocate. Population density, air and water pollution, and the budget allocated to natural resources, parks, and recreation are integral considerations in the ranking by various private organizations of U.S. cities as to their desirability as environments in which to live, work, and raise children.

In one environmental ranking, the Houston Statistical Metropolitan Area was ranked 74 out of 75, with 75 being the worst.[49] Houston was ranked 3.4 (between "warning" and "danger") relative to environmental stress, and was ranked 187th of 195 cities (with 195 being the worst) and 239th of 239 metropolitan areas (with 239 being the worst) for social, economic and environmental factors that affect children.[49, 73] More recently, in the 1998 *Money* magazine's annual poll, its readers named clean air and clean water as the two most important characteristics in choosing where to live. Clean air and water were more important than 39 other characteristics, including low crime rate, good schools, low housing prices, and plentiful doctors.[11] The quality and amount of green space were factors in each of these environmental rankings.

Trees Increase Tourism & Convention Business

Tourism and convention business can bring millions of dollars into an area and are, in addition, "industries" that are not only low-polluting but provide valuable public relations. The Houston area is largely perceived, rightly or wrongly, as one of the best examples of urban sprawl: a wasteland of concrete, spreading malls, asphalt parking lots, endless freeways, and cacophonous billboards. In a recent newspaper article, successful attempts by voters in Southern California and elsewhere to control urban sprawl were described by *Washington Post* reporter William Booth as attempts to make communities "look more like Europe and less like the 610 loop around Houston."[19]

When families plan vacations and members of large organizations decide where to hold their next meetings, important considerations are recreational facilities, parks, efficient and clean public transportation, museums, cultural events, price of convention and hotel facilities, sports, pedestrian friendliness, and visual attractiveness. Cities like Seattle, Chicago, Toronto, Atlanta, New Orleans, San Francisco, Cincinnati, Baltimore, and Boston often top the list not because they are the cheapest (they're not), but because they have the facilities, the parks, the transportation infrastructure, and a pedestrian-friendly environment.

And yet the Houston area has museums and cultural attractions equal to any city in the nation. It is home to major universities and some of the world's foremost medical and scientific establishments. It also lies at the heart of one the most complex and fascinating ecosystems anywhere, being the meeting point for the coastal estuaries and Gulf of Mexico to the south, the Canada-to-Mexico bird and butterfly migrational route through the Katy Prairie to the west, the pine forests to the north, the Columbia bottomlands to the southeast, and the Big Thicket to the northeast — all tied together by a complex river and bayou system.[33] This ecosystem is an extraordinary resource for the area, one that even now is bringing millions of dollars into the local economy as birdwatchers from around the world annually converge on the Katy Prairie and other nearby migrational sites. More attention to and protection of these ecological treasures would benefit the area not only aesthetically, but economically.

Trees Provide Educational & Health Benefits

Parks, urban forest, arboretums, and greenbelts provide areas in which urban residents and visitors can exercise, learn about area fauna and flora, and escape from the traffic, noise, and stress commonly associated with urban life. Residents are healthier in cities in which walking and biking to work are emphasized;[18] they are exposed to less pollution,[28] are less likely to be overweight, and have lower levels of frustration and negativity[18] than those who commute by car on congested roadways. In addition, studies have shown that walking or riding a bike to work adds, on average, two years to one's life span, reduces absenteeism due to illness, and increases worker productivity.[18]

Conversely, the absence of green space can lead to increased physiological and psychological stress, increased violence and a more vulnerable immune system.[30, 50, 59, 91] In one study, patients assigned to a room with a window that looked out on a natural tree-filled setting had shorter postoperative hospital stays, received fewer negative evaluative comments in the nurses' notes, and took fewer analgesics than matched patients in similar rooms that faced a brick building wall.[135]

Trees Provide Urban Habitat & Encourage Biological Diversity

Urban growth severely threatens indigenous flora and fauna. Decrease in native species through habitat fragmentation, alteration, or pollution may create overpopulation of other species, thereby disrupting the delicate ecological balance necessary for a healthy ecosystem. For example, destruction of habitat for native birds, toads, foxes, bats, insects, and other predator species may contribute to increases in rats, mice, mosquitoes, and other potential disease vectors in urban settings. Soil compaction, changes in runoff, and cutting down trees or clearing undergrowth may similarly change the natural plant populations. In the Houston metropolitan area, for example, ragweed prospers in compacted, eroded, abandoned urban lots and along rights-of-way.

The effects of pesticides and other pollutants may damage higher life forms and predator species preferentially, favoring increases in species with shorter life spans and higher reproductive rates that can adapt more readily. Some species, such as ragweed, rats, termites, bagworms, and mosquitoes, may overpopulate, becoming management problems. Spokespersons for the Harris County Mosquito Control Division note that resistance to the organophosphate malathion has rendered use of this insecticide increasingly ineffective against area mosquitoes.[105] They attribute this particular resistance primarily to the large amounts of organophosphates, such as Diazinon™ and Dursban™, used by homeowners to control lawn and garden insects.

Exotic or nonnative plants, animals or insects may prosper in the absence of natural controls or in degraded urban habitats in which native species are threatened. In the Houston metropolitan area, fire ants and Chinese tallow are introduced species that have prospered and now threaten native species.[22, 69] Intensive pesticide programs are currently used against both area fire ants and Chinese tallow. These pesticide programs add to the toxicological burden borne by area residents and ecosystems.

Programs that promote the health of trees and other vegetation by protecting good-sized and preferably connected areas of green space, by emphasizing low-maintenance native species, and by safeguarding healthy soil and the microbes necessary for healthy plants, provide a habitat for the turtles, frogs, toads, geckos, chameleons, raccoons, squirrels, earthworms, foxes, deer, bees, butterflies, birds, and other living things that help maintain a sustainable ecological system.

Trees Are a Renewable Resource

Animals, including humans, are critically dependent on healthy plants for their existence — for food, shelter, medicines, shade, oxygen, energy. Contrasted with oil and gas which, although originally derived from plants, are for all practical purposes finite sources of fuel for energy, trees and other vegetation — if properly protected, harvested, and used with care — provide a renewable source for energy, building materials, furniture, medicine, books, newspapers, and food. Recently in London the Anglo-Dutch oil company Royal Dutch/Shell Group announced that it was investing $500 million in renewable energy, including plantations that would supply timber, also known as biomass, to burn for electric power. Shell notes that its long-range planning suggests that by 2050 “the world energy consumption of biomass for electricity generation will equal that of gas and oil today.”[10] Although the use of renewable biomass for energy is preferable to the extraction, refining, and transport of oil and gas, combustion creates considerable air pollution. From the point of view of air pollution, solar and wind power are generally preferable where feasible.

As a renewable resource, trees also provide jobs associated with sustainable forestry, including producing seedlings, planting, harvesting, transport, and utilizing the end product. Within an urban area such as Houston, protecting trees and enlarging areas of green space provide jobs for urban planners, foresters, landscape architects, tree doctors, lawn and garden workers, and many others.

Air Pollution-Induced Damage to Trees and Other Area Vegetation

Like people, plants experience physiological stress from a number of sources, including air pollution, drought, insufficient nutrients, and ultraviolet radiation, alone or in combination.[12, 55, 62, 64, 72, 84, 104, 109, 127, 133, 137, 147] Although plants are very effective in removing ordinary amounts of pollution, they too become stressed and may die under the assault of high levels of pollution.[123] In the Appalachian forests and elsewhere, decades of air pollution have so weakened the trees that they are no longer able to resist insects and diseases the way healthy trees can, and are dying in unprecedented numbers.[13] In cities where trees are subjected to multiple anthropogenic stresses, including concrete, pollution, increased heat, pesticides, herbicides, fertilizers, and lack of adequate root zones, the assault shortens the life of trees significantly. The average tree in a downtown area lives 7 to 10 years and elsewhere in a city 32 years; the same tree on a rural site would live an average of 200 years.[6]

The man-made air pollutants recognized as causing the most damage to trees and other vegetation are ozone, nitrogen dioxide, and sulfur dioxide. Other common pollutants associated with direct plant damage include fluoride, heavy metals, ammonia, chlorides, NO_x, particulates, and ethylene.[94] Man-made air pollutants that indirectly affect trees and forests include chlorofluorocarbons, which decrease the protective stratospheric ozone layer thereby increasing the amount of damaging ultraviolet radiation to which plants are exposed, and excess carbon dioxide which modifies the environment of trees and other vegetation.[52]

The effects of ozone pollution on area vegetation are significant and will be later addressed. Damage from nitrogen and sulfur dioxides (or in other forms, such as sulfate, peroxyacetyl nitrate, or sulfuric and nitric acids) is somewhat less severe here than in parts of Europe and the eastern United States, but is still a major factor in the health of area vegetation. Both pollutants are emitted during the combustion of fuels, with cars, trucks, and industrial processes being major sources.

Sulfate primarily lowers the soil pH, whereas nitrate not only lowers the soil pH but acts as a nutrient, stimulating leaf and twig growth and leading to faster consumption and depletion of nutrients.[52] This excess nitrogen makes trees less tolerant of cold, and a lowered soil pH inhibits root growth, making trees more susceptible to drought. In addition, excess nitrogen in the sap and leaves attracts insects. Cutting down and removing trees also lead to lower soil pH because when trees die naturally they return base cations to the soil. In areas where trees are removed rather than being allowed to decay naturally, the pH of the soil is lowered.[52]

Nitrate and sulfur are also deposited on leaves and branches directly and, dissolved in rain and snow, delivered as nitric and sulfuric acids. This can lead to direct injury to tissues, as well as lowering the soil pH. Although individual plants may respond somewhat differently, accumulation of sulfite in tissues generally produces a chlorotic appearance of the leaf and a silvering or bronzing of the undersurface. Acute exposure leads to necrotic areas and dropped leaves.

Nitrate generally produces a glazed appearance of the leaves, and a silvering of the undersides, followed by bronzing after two to three days.[129] Photosynthesis may be compromised, and plants will often try to compartmentalize damage by walling off the injury. This stress makes trees and other vegetation more vulnerable to disease and insects. Alfalfa, bean, and cotton crops are especially sensitive to sulfur compounds, whereas azaleas, beans, and hibiscus are especially sensitive to nitrogen compounds.[129]

Hydrocloric acid mist causes acid-burnt dark patches on leaves, whereas chlorine stipples the upper leaf surface very much like ozone injury.[94] Exposure to ethylene brings about a variety of abnormal growth processes, including premature defoliation. Exposure to fluoride, which is released during many manufacturing processes, leads to a characteristic water-soaked discoloration of leaves, followed by browning.[94]

Economic Impact & Mechanisms of Ozone Damage

The high levels of ground-level ozone pollution to which area trees, ornamentals, and crops are exposed during the peak of the summer growing season result in considerable plant damage and economic loss. Four visible symptoms may result from ozone exposure: (1) localized thickening and sharply defined small dot-like lesions (the most common symptom), (2) general upper surface bleaching, (3) large necrotic white-to-red areas, and (4) general chlorosis or chlorotic flecks.[129]

Nationwide, ozone pollution is estimated to cause $2 to $3 billion worth of crop loss annually,[58, 121] and to cost $1.5 to $3.9 billion in damage to paint, rubber, and other surfaces.[61, 78] The National Crop Loss Assessment Program has determined that current levels of ozone pollution cause reductions in crop yields of 10% for soybeans, 14% to 17% for peanuts, 7% for turnips, 53% to 56% for head lettuce, and 2% for red kidney beans.[58] Alfalfa, beans, oats and onions are also particularly sensitive to ozone.[129] Economic analyses have indicated that the benefits to society of moderate (25%) ozone reductions, in terms of reduced vegetation damage, would be approximately $1.7 billion.[123]

Although discoloration and crop loss are the visible signs, the real damage is at cellular and genetic levels and disrupts all aspects of plant function. Ozone enters tree leaves through the stomata, attacking the cells inside the leaves. In response, chlorophyll is often destroyed, photosynthesis rates are reduced, more sugars are retained in the leaves, and less starch is transported to the roots. As a result, insects are attracted to the leaves and the trees do not have sufficient starch reserves in their roots to survive repeated defoliations. The trees are also unable to supply the microbes in their root zones with the carbohydrates they require. One serious consequence is that needed nutrients in the root zone are no longer available for the trees.

Economic analyses have indicated that the benefits to society of moderate (25%) ozone reductions, in terms of reduced vegetation damage, would be approximately $1.7 billion.

As noted earlier, photosynthesis is especially sensitive to ozone. Both short-term (hours) and long-term (weeks) exposure of plants to either 200 or 100 ppb of ozone reduces photosynthesis measurably.[42] This is thought to be the result of damage to the photosynthetic system,[29] CO_2 fixation sites,[106] chlorophyll pigment system,[113] electron transport process,[118] or cell membranes. Growth reductions and impaired photosynthesis in sensitive birch trees following exposure to ozone have been observed to be related to ultrastructural injuries, especially those involving the chloroplasts.[103]

Considerable variation exists among plant species in their ability to cope with increased levels of ozone.[32, 112] Guidi and associates reported a strong reduction in photosynthetic activity in two clones of poplar — one resistant and one sensitive to ozone — that were fumigated with 150 ppb ozone for five hours.[55] Although the resistant poplar rapidly recovered when the ozone was removed, the effect was irreversible in the sensitive poplar. Anttonen and associates reported visible injury and changes in the starch contents and stomatal conductance (the amount of uptake through the stomata, which is determined largely by the time and degree to which the stomata are open) of Aleppo pine needles following ozone exposure.[12]

The 24-hour pattern of ozone uptake in the forest appears to be significantly influenced by stomatal conductance. In one study, different birch clones revealed substantial differences. Clone A showed high stomatal conductance (that is, it kept its stomata open) during the day, whereas clone B (characterized as a lazy birch) kept its stomata closed during day and more open during the night.[72] Plants with high stomatal conductance during the day would be expected to experience more ozone damage because ozone levels generally peak during the early afternoon.

The presence of excess ozone-induced oxygen radicals is generally considered to be the primary cause of damage, although oxygen radicals are also formed during normal cell metabolism and their production and destruction are regular cellular phenomena.[71] Plants use various mechanisms, including protective enzymes and antioxidants, to attempt to limit the damage caused by ozone-induced oxygen radicals.[46] Increases in antioxidants, including ascorbate, tocopherol, and glutathione, have been observed in leaf tissue following ozone fumigation.[93] Plants, like people, are often unable to properly repair or limit oxygen-radical damage. Over time such damage leads to DNA damage and increased cell death.

Studies of spruce trees revealed genetic changes (including chromosomal stickiness, aberrant DNA links, clumped metaphases, amorphous chromatin masses, and chromosome breaks) in the root tips after exposure of the trees to approximately three months of moderate ozone.[97] Wonisch and associates investigated the relationship between ozone and chromosomal aberrations in the root tip meristems (actively dividing and growing tissue) of young spruce trees.[147] They found a dose-dependent increase in chromosomal aberrations, some of which appeared to accelerate cell death.

In urban forests, trees are often exposed to ozone and drought simultaneously during the summer.[87] Paakkonen and associates exposed birch sapling clones simultaneously to drought and ozone.[104] Visible leaf injuries, including yellowing of leaves, were observed. In addition, ozone induced severe swelling and curling of the chloroplast organelles and caused increased disintegration of the mitochondria.

Trees and other vegetation are typically exposed to other air pollutants simultaneously with ozone.[116, 148] Exposure to multiple pollutants generally exacerbates the injury observed. For example, although increased CO_2 alone promotes growth, elevated ozone levels reduce plant growth regardless of the CO_2 concentration, and the ozone injury is usually worse when elevated CO_2 levels are present.[14, 79, 108]

Ozone also impacts the growth of trees. The height of plane trees grown in a greenhouse with ambient Washington, D.C., air was demonstrated by Santamour and co-researchers to be only 75% of the height of similar trees grown in filtered air.[123] Jensen and associates treated silver maple and eastern cottonwood seedlings with 0, 100, 200, or 300 ppb of ozone for 12 hours per day for 60 days, and found that leaf-area expansion and leaf-weight rates declined with increasing ozone exposure.[123]

Increased Biogenic Emissions?

A research area that has received scant attention is the effect of man-made pollution on biogenic emissions. There is substantial evidence that man-made pollution, over time, damages a plant's photosynthesis mechanisms, decreases crop yields and forest growth, makes plants more susceptible to disease and insect damage, and leads to increased plant mortality. The fact that biogenic emissions, particularly isoprene, correspond to the rate of photosynthesis suggests that biogenic emissions are reduced in areas with significant man-made pollution. However, there is also evidence that biogenic VOC emissions are increased, at least transiently, in plants under stress.

As noted earlier, plants, especially trees, manufacture and emit VOCs in part to create a microenvironment that is conducive to its well being. Plants, like humans, have genes that are stimulated (upregulated) during times of stress to increase the production of various proteins, such as the heat shock proteins, which in turn may help protect the organism directly or may stimulate various secondary responses, such as increasing the metabolic rate to provide more food, initiating premature death of damaged tissue, and secreting VOCs and other substances to better control the microenvironment.

Biogenic VOCs are emitted when a plant is injured or cut, probably to ward off infection. Because ozone and other pollutants physically injure plants, it is not unreasonable that plants would respond, at least initially, by increasing their emissions in order to ward off infection or to detoxify the assailant in some way. Isoprene and the monoterpenes are highly reactive, and it may be that some of the man-made pollution in the immediate vicinity of a plant can be chemically deactivated.

A number of studies have demonstrated that stress has an effect on the emission rates of biogenic hydrocarbons.[41, 115, 119] For isoprene, the plant enzyme isoprene synthase is thought to be play a major role in the changes observed in isoprene emissions in response to various environmental cues. The role of this enzyme is currently an active area of research.[41] Schuh and associates exposed sunflowers and tobacco plants to between 30 and 120 ppb of ozone and found an increase in monoterpene emissions beginning between 3 and 24 hours after exposure.[119] These studies suggest that anthropogenic pollution itself changes the rate and possibly the character of biogenic VOCs. This is an area that needs additional study.

What Other Areas Are Doing

Urban Ecological Analysis

American Forests has developed a technique, called Urban Ecosystem Analysis (UEA), that uses satellite imagery, aerial photographs, and CITYgreen software to map, measure, and calculate the economic benefits of urban trees in a community.[5, 7] Using broadly accepted methodology, the analysis places a dollar value on the benefits the urban forest provides in terms of (1) air quality, (2) energy conservation, and (3) stormwater runoff reductions. The analysis also assesses the health and composition of the urban forest and models a variety of development options. Among urban areas for which American Forests has conducted an UEA are Atlanta, Georgia; Dade County, Florida; Milwaukee, Wisconsin; and Austin, Texas. Selected findings include the following:

- Since 1972 Atlanta's undeveloped landscape has decreased by 60%, creating an expanding heat island complex, with summer temperatures in developed areas 12^{o}F warmer than in the countryside (Figure 9). The heat island effect is thought to be responsible for 12% of Atlanta's air quality problem.[7]
- In Dade County, 90% of homes have air conditioning but only 10% have optimally placed trees. Replacing residential palm trees with Live oaks would increase energy savings by 20% and reduce stormwater runoff by 8%.[7]
- Austin's trees reduce stormwater peak runoff by 28% (a value of $122 million).[7]

The UEA is being used to help urban planners utilize urban forests not only to improve urban quality of life, but also to save taxpayers money. American Forests recommends a tree canopy goal of 40% for urban areas, with approximately a 15% canopy in business districts, a 25% canopy in urban residential areas, and a 50% canopy in suburban areas.[6] The current tree canopy in the Houston area has not been calculated.[3]

Cost/Benefit Analysis of Trees: Fort Worth

In 1997 The Davey Resource Group, with the cooperation of the City of Fort Worth, the Parks and Community Services Department, the Texas Utilities, and the Texas Forest Service, conducted a cost/benefit analysis of the urban forest in Fort Worth in order to help city planners develop a comprehensive urban forest plan.[131] Data collected included urban forest cover (from satellite images and ground surveys), tree program costs, and community characteristics such as pollution levels, precipitation, and utility costs. Data were analyzed using QuantiTree 2.0 benefit and cost analysis software. An interesting aspect of this analysis is that it defined Fort Worth's urban forest in terms of location — street, yard, park/transportation corrider, vacant/wild, commercial/industrial, and institution — as these categories defined similar tree types and management costs.

The benefits analyzed included reduction of air pollution (PM_{10}, NO_2, CO, SO_2 and O_3), carbon uptake, stormwater management, energy savings, and appraised value. Costs included tree planting and maintenance. The average tree cover in Fort Worth is 24%. The total economic benefit of all trees in Fort Worth for 1996 was about $77 million, with the greatest benefit from reduced energy costs, followed by reduced stormwater runoff (Table 6). Removal of particulates was the primary air quality benefit (Table 7). The benefits outweighed the costs for all locations, with the greatest benefit seen in the park location, where the benefits outweighed the costs by a factor of 28 due largely to low maintenance expenses. The final recommendations included (1) conserve existing trees; (2) select and locate trees to maximize benefits; (3) aim for species and age diversity to control maintenance costs; and (4) educate and involve community leaders to lower costs through volunteer efforts.

Mexico City's Tree Planting Program

The Mexico City metropolis, with its population of 25 million and surrounding mountains that frequently trap emissions, has some of the worst pollution on earth. In its fight against air pollution, Mexico City can boast of one of the most extensive and best maintained public transportation systems in the world, a large park system, a program (Hoy No Circula) that keeps approximately one-fifth of area vehicles off the road on any given day, and a comprehensive contingency plan that removes another 20% of vehicles from the roads, stops road construction, shuts down approximately 40% of industrial sources, and keeps school children inside on days when ozone levels reach 240 imeca (approximately 0.26 ppm — Mexico City had only one such episode in 1998). In addition, Mexico City began this year to plant what will become a 500-square-mile environmental forest on the southern rim of the metropolitan area — the largest reforestation project ever undertaken for environmental purposes. An Alabama-

	Street	Park	Yard	Vacant	Comm	Instit	TOTAL	PERCENT
Air Quality	19	122	411	294	64	43	**953**	**1.23**
Carbon	11	77	231	182	37	25	**563**	**0.73**
Stormwater	557	752	7,926	1,792	2,174	1,209	**14,410**	**18.62**
Energy	1,415	7,348	29,060	13,409	6,777	3,464	**61,473**	**79.42**
TOTAL	**2,002**	**8,299**	**37,628**	**15,677**	**9,052**	**4,741**	**77,399**	**100.00**

Table 6. Estimated 1996 economic benefits produced by the tree cover in Fort Worth, Texas (in thousands of dollars), by location.[131] The benefits are based on 1) the interception and absorption of key pollutants, 2) the removal of CO_2 from the air and storage as carbon, 3) the interception and storage of precipitation by tree canopies, and 4) the lowering of summer-time temperatures.

	Street	Park	Yard	Vacant	Comm	Instit	TOTAL
Air Quality (tons)							
PM10	12.1	75.8	255.6	181.8	39.6	26.8	**591.7**
NO2	0.3	2.3	6.8	5.4	1.1	0.7	**16.6**
CO	0.0002	0.0014	0.0041	0.0033	0.0007	0.0004	**0.0101**
SO2	0.3	1.8	5.5	4.3	0.9	0.6	**13.4**
Ozone	0.6	3.9	11.7	9.2	1.9	1.2	**28.5**
Carbon (tons)	424.6	2,186.5	6,588.5	5,213.9	1,054	703.6	**16,171.1**
Stormwater (1,000 gal)	55,779	75,152	792,583	179,205	217,366	120,913	**1,440,998**
Energy (1,000 kWh)	16,579	86,072	340,406	157,075	79,385	40,571	**720,088**

Table 7. Estimated 1996 benefits from trees in Fort Worth, Texas, by location, according to the quantity of 1) pollutants removed, 2) CO_2 stored as carbon, 3) precipitation intercepted, and 4) energy saved due to lower temperatures.[131]

based company will establish and operate a state-of-the-art nursery that will supply approximately 150 million seedlings for the project. The forest is expected to remove thousands of pounds of pollutants from the air every year.[9]

Cool Communities Program

The rising temperature in cities is quickly becoming a major health and economic problem. A number of cities have enthusiastically embraced the Cool Communities Program (jointly sponsored by American Forests and the Department of Energy) or similar programs. Such programs emphasize the use of reflective, light-colored surfaces (albedo technology), a reduction in the use of asphalt and concrete, and an increase in trees and other vegetative ground cover. Eight communities, including Austin, Atlanta, Tulsa, and Tucson, are currently planting trees as part of the Cool Communities Program and are monitoring the results.

Sacramento, CA, is partnering with NASA, the Environmental Protection Agency, and the U.S. Department of Energy to study how strategically placed urban forests and the use of reflective surfaces can help cool the city, reduce air pollution, lower energy bills, modify growth plans, and help mitigate further deterioration of air quality.[86] A program to plant 500,000 trees in Sacramento has already begun.[92]

Greenbelts

Many studies have demonstrated that respiratory symptoms and asthma in urban residents, especially children, often correlate with the nearness of home or school to traffic, and that significantly increased levels of pollution can be measured for at least 300 meters (approximately three football fields) from either edge of a street or highway with significant traffic.[21, 34, 37, 95, 138, 141] In the Houston area many people live and work within 300 meters of traffic. A band of trees on both sides of our freeways would significantly reduce the amount of pollution that reaches these vulnerable areas, while at the same time considerably improving the visual appeal of the freeways.

Greenbelts can also be used to connect park areas, to develop hike and bike systems, and to reduce the impact of major industrial sites on nearby residential areas. The use of greenbelts around industrial sites has been shown to reduce the exposure of nearby residents to industrial pollutants significantly,[123] as well as to slow the movement of toxic chemicals into residential areas in the event of an accidental release. Greenbelts are also being used to help stabilize rainfall, which decreases or becomes erratic when trees are removed for agriculture or development. In the Great Plains of the U.S., tree planting is being used to reduce recurring droughts and to improve the climate for farming. Organized greenbelt programs are being implemented in a number of U.S. cities, including Washington, D.C., Boston, Seattle, and San Francisco, and have been used in Europe for years.

Smart Growth Programs

In order to limit urban sprawl and the pollution, heat, and car-dependent culture that such growth creates, many areas are voting into existence smart growth or slow growth initiatives that create urban growth boundaries and protect undeveloped land. In November 1998, the citizens of Ventura County, CA, created urban boundaries around all of the county's major and smaller cities, and enacted legislation that declares that agricultural and rural lands cannot be re-zoned for development without approval of the voters.[19] The San Francisco Greenbelt Alliance has similarly and successfully pushed for urban growth boundaries around 15 cities in the region. Indeed, nearly 200 anti-sprawl initiatives were on the ballot in November 1998 and the majority passed, including a vote in New Jersey to spend $1 billion to protect the state's farms and forests — nearly one-half of New Jersey's undeveloped land.[19]

Where Do We Go From Here?

In the greater Houston area a number of groups — including Trees for Houston, the Bayou Preservation Association, the Park People, the Katy Prairie Conservancy, and Treescape, among others — are currently working on various projects to protect or restore area vegetation and ecosystems. However, there has been no study of the benefits of increasing the region's forest cover as has been done in Fort Worth, Austin, Atlanta, and elsewhere; no comprehensive inventory of existing vegetation such as was done in the Chicago area has been done here; and no long-range or comprehensive urban forestry plan has been developed for the eight-county area.

This lack of a vision for Houston means that, although many well-intentioned efforts are proceeding, there is no articulated goal defining the ideal Houston or directing the variety of current efforts. Projects include (1) the downtown Cotswold Project, which will plant trees, build fountains, and widen sidewalks to encourage walking; (2) the 380-mile Houston Bikeway Program, which began construction on its first segment in October 1998; (3) various projects by Trees for Houston, including planting 300 trees (mainly Live oaks and Chinese elms) along Hillcroft-Voss between the Southwest Freeway and Woodway, planting trees along the rights-of-way of all parkways in Houston, planting trees at 20 area schools, planting 60 large Laurel oaks along Texas Avenue between Bayou Place and Main Street, and efforts to reforest U. S. 59 between Shepherd and Beltway 8, and Interstate 45 between the downtown and Loop 610;[23] and (4) many smaller programs by area neighborhood and business associations.

Although no smart growth initiative has yet made the ballot in the Houston area, the heat island effect and growing voter dissatisfaction with the lack of long-range planning have spurred recent discussions within various governmental and institutional circles, including the City of Houston, the Houston-Galveston Area Council, the Citizens' Environmental Coalition, and the Houston Environmental Foresight Program (a program of the Houston Advanced Research Center), about defining a "vision" for the area and ways of attaining such a vision. In these discussions, the concepts of smart growth and sustainable growth have begun to be explored.

The absence of a regional urban forest plan has serious consequences. Expanding freeways and sprawling business and residential development continue to devour immense tracts of land — raising area temperatures, increasing urban sprawl, increasing area flooding, and fragmenting and often irreparably damaging the ecological underpinings of the region. For many years the Houston area has grown and prospered as a mecca for rampant development, often with little regard for quality of life, and in the absence of any long-term plan for the area. Increasingly we hear that this is not what area residents want, that such an environment will neither keep our best and brightest nor attract the best and brightest to the region. It is time for the Houston region to imagine what it would like to be, and then gradually put into place the programs to get us there. There is little doubt, in speaking with area residents, that — like residents throughout the U.S. — they value clean air and water, parks and trees, and that most, given attractive alternatives, would love to avoid the freeways and leave the driving to someone else. A significant increase in the urban forest would do more to improve the visual appeal and comfort of Houston, for less money, than any other project.

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Selected Resources

Alliance for Community Trees
201 Lathrop Way, Suite F
Sacramento, CA 95815
(800) ACT-8886; Fax (916) 924-3803
email: ACT@MacNexus.org
http://www.treelink.org/connect/orgs/act

American Forests (formerly the American Forestry Association)
P.O. Box 2000
Washington, DC 20013
(800) 368-5748; Fax (202) 955-4588
http://www.amfor.org

American Society of Landscape Architects
Houston/Gulf Coast Section
3701 Travis
Houston, Texas 77002
(713) 521-1558
email: sslaney@slaney.santana.com

Armand Bayou Nature Center, Inc.
8500 Bay Area Blvd.
P. O. Box 58828
Houston, Texas 77258
(281) 474-2551; Fax (281) 474-2552
http://www.ghgcorp.com/abnc

Austin, City of
Austin Parks and Recreation Department
Jan Fulkerson, Urban Forestry Board
2525 S. Lakeshore Blvd.
Austin, TX 78741
(512) 440-5150

Bayou Preservation Association, Inc.
P.O. Box 980863
Houston, Texas 77098
(713) 529-6443; Fax (713) 529-6481

Citizens' Environmental Coalition
P.O. Box 27579
Houston, Texas 77227-7579
(713) 524-4232; Fax (713) 529-9426
email: cec@space.rice.edu
http://space.rice.edu/~cec

Fort Worth, City of
Parks and Community Services
Harold Pitchford, City Forester
4200 S. Truing, Suite 2200
Ft. Worth, TX 76115
(817) 871-5728

Friends of Hermann Park
P.O. Box 541447
Houston, Texas 77254-1447
(713) 524-5876; Fax (713) 524-5887
email: fhp@neosoft.com
http://www.neosoft.com/~fhp

Galveston-Houston Association For Smog Prevention (GHASP)
2476 Bolsolver, Box 126
Houston, Texas 77005
(713) 528-3779; Fax (713) 538-4042
email: ghasp@neosoft.com
http://www.neosoft.com/~ghasp

Harris County Tree Registry
http://www.parkpeople.org/registry/registry.html

Houston Arboretum & Nature Center
4501 Woodway Drive
Houston, Texas 77024
(713) 681-8433; Fax (713) 681-1191

Houston Area Urban Forestry Council
6501 Memorial Drive
Houston, Texas 77007
(713) 880-8374

Houston, City of
Department of Parks and Recreation
Victor Cordova, Urban Forester
6501 Memorial Drive
Houston, TX 77007
(713) 867-0378; Fax (713) 867-0381

Houston-Galveston Area Council (H-GAC)
Geographic Information System (GIS)
P.O. Box 22777
3555 Timmons
Houston, Texas 77227-2777
(713) 627-3200; Fax (713) 993-4508
http://www.hgac.cog.tx.us/intro/introcegis.html

Katy Prairie Conservancy
72210 Oak Road, Suite 230
Katy, Texas 77494
(281) 391-7116; Fax (281) 391-7339

Mercer Arboretum & Botanic Gardens
22306 Aldine Westfield Road
Humble, Texas 77338
(281) 443-8731; Fax (281) 443-6078

Native Plant Society of Texas
Glenn Olsen, President
P.O. Box 721356
Houston, Texas 77272-1356
(281) 495-8144

The Nature Conservancy of Texas
P. O. Box 3864
Houston, Texas 77253-3864
(713) 853-5634; Fax (713) 646-8329

The Park People, Inc.
Glenda Barrett, Executive Director
P.O. Box 980863
Houston, Texas 77098-0863
(713) 942-7275; Fax (713) 942-8429
email: park@neosoft.com
http://www.parkpeople.org

Ozone Transport Assessment Group (OTAG)
Technical Reports
http://capita.wustl.edu/otag/Reports/Reports.html

Piney Woods Conservation Center
Route 1, Box 138DE
Broaddus, Texas 75929-9715
(409) 584-2412; Fax (409) 584-3275

Radian International LLC
8501 N. Mopac Blvd.
P.O. Box 201088
Austin, TX 78720-1088
(512) 454-4797; Fax (512) 454-7129
http://www.radian.com

Rice University
GIS Information Center
Pat Hebert
Geology & Geophysics
6100 Main, MS 126
Houston, Texas 77005
http://riceinfo.rice.edu/Fondren/GDC

Texas Department of Parks & Wildlife
4200 Smith School Road
Austin, Texas 78744
http://www.tpwd.state.tx.us

Texas Forest Service
Forest Resource Development Department
3rd Floor, John B. Connally Building
301 Tarrow Drive
College Station, Texas 77843-2136
(409) 845-2641; Fax (409) 845-5764

Texas Natural Resource Conservation Commission (TNRCC)
Mark Estes [biogenics modeling]
Office of Air Quality
Air Quality Planning and Assessment Division
P.O. Box 13087
Austin, TX 78711-3087
(512) 239-6049; Fax (512) 239-1123
http://www.tnrcc.state.tx.us

TreeScape
[Implementation of Houston's Tree and Shrub Ordinance]
Mickey Merritt, Coordinator
P.O. Box 980863
Houston, Texas 77098-0863
(713) 942-0587; Fax (713) 942-8429
email: treescp@neosoft.com
http://www.parkpeople.org/frames.html

Trees for Houston
Katharine Lord, Executive Director
P. O. Box 13096
Houston, Texas 77219
(713) 840-8733; Fax (713) 840-8734
email: trees@neosoft.com
http://www.treelink.org/connect/orgs/act/houston.htm

United States Department of Energy
Center of Excellence for Sustainable Development
Land Use Planning Strategies: Urban Forest
http://www.sustainable.doe.gov/landuse/urbanfor.htm

The University of Texas at Austin
Professor David Allen
Department of Chemical Engineering and
Center for Energy Studies
Austin Texas 78712
(512) 471-0049; Fax (512) 471-7060
email: allen@che.utexas.edu

Urban Harvest
PO Box 980460
Houston, Texas 77098
(713) 880-5540; Fax (713) 880-5545
email: urbanharve@aol.com

White Oak Bayou Association
P.O. Box 920510
Houston, Texas 77292-0510
(713) 520-0280; (713) 739-6836

The Woodlands GREEN
P.O. Box 9934
The Woodlands, Texas 77387
Voice Mail: (281) 367-1271, x246