Casey Trees White Paper

Benefits of the Urban Forest Literature Review

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Abstract

The scientific literature was reviewed to assess the current scientific knowledge of urban forest benefits. Benefits were arranged into categories of Economic, Psychosocial and Wellness, Environmental, Public Health, and Other. A section also details community concerns with trees and explores the perceived disadvantages or conflicts of urban trees.

Each section in this literature review is organized to stand alone, providing a comprehensive overview of the relevant literature for the topic and a brief summary. The references for the section are at the end of the section in order presented. The comprehensive list of literature reviewed is at the end of the paper, in Appendix A, alphabetically by author.

The primary source of the literature is the on-line Electronic Journal Library of the University of Washington in Seattle, WA, USA. Journals were reviewed through September 2003 and accessed via on-line libraries such as PubMed, Ingenta, Elsevier, and individual search engines of journals such as *Science, Nature* and *American Journal of Public Health.* Approximately 400 papers were reviewed and 275 directly cited in this paper. A number of non-journal publications were cited, such as commentaries or newspaper articles, to provide context or additional information. In addition, the forestry library database at the University of Minnesota in St Paul, MN, USA is an excellent resource. Lastly, the United States Forest Service has outstanding field offices that produce robust empirical research in urban forestry: two such offices are the Center for Urban Forest Research in Davis, CA, USA, and the Northeast Research Station in Syracuse, NY, USA.

Editors and authors have also kindly reproduced articles not available electronically and these hard-copy papers are at Casey Trees. A large number of the papers reviewed are held in electronic file format at Casey Trees as well.

Any errors in interpreting the literature are the fault of the author alone.

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Introduction

The urban forest is the most commonly visited forest in the United States, far outstripping visits to our National Parks and National Forests. Almost one-half of the human population worldwide lives in an urban area, and the figure for the United States is far higher, perhaps 80%[1]. Urban areas currently cover approximately 3.5 percent of the total land area in the conterminous United States. Urban areas in the conterminous United States doubled in size between 1969 and 1994. Future projections are for a likely increase in the ratio of urban to rural populations. Urban areas contain approximately 3.8 billion trees with an average tree canopy cover of 27 percent[2] . European urban forest coverage is similar to the United States' in that the coverage varies widely according to climatic region.

Urban forestry is a relatively young discipline, with papers falling under the 'urban forestry' rubric since the mid-1970s. Early journal and proceedings papers were generally concerned with amenity values such as recreation and social comforts, or concerned with silvicultural aspects such as selection, physiological responses and hydrological and noise impacts. As the discipline grew and expanded in the 1980s, more papers and contributions appeared that expanded the scope of urban forestry. Studies appeared that explored how the urban forest can save energy, cast shade, provide economic values. Detailed silvicultural topics were developed such as site selection, best species by region, sophisticated pest management, and the first computer programs for urban foresters. The 1990s saw a veritable explosion of activity, with robust papers in energy savings, cost-benefit analyses, hydrology, human wellness hypotheses, community forestry, and many other topics seen today.

Today, urban forestry is an increasingly recognized component of the urban infrastructure, and is frequently called 'green infrastructure'; contrast 'green infrastructure' with 'grey infrastructure':

> A community's green infrastructure is made up of trees, shrubs, open spaces, and soils, while gray infrastructure consists of roads, sidewalks, buildings, and utilities. Structure and functions of gray and green infrastructure are extremely different. Green infrastructure is porous: it allows water to soak into soil. It is called green because it hosts living plant material, the largest of which is trees[3] .

Whereas the United States Environmental Protection Agency explored a different definition:

> Green infrastructure is our Nation's natural life support system-an interconnected network of waterways, wetlands, woodlands, wildlife habitats, and other natural areas; greenways, parks and other conservation lands; working farms, ranches and forests; and wilderness and other open spaces that support native species, maintain natural ecological processes, sustain air and water resources and contribute to the health and quality of life for America's communities and people.[4]

Although the general public may appreciate the aesthetic beauty and shade cast by the urban forest, the urban forest canopy is decreasing in area in many parts of the United States. The built environment separates many people from the natural environment - thus, many benefits of the urban forest go unknown. And urban foresters must work hard to enumerate all the varied benefits of the urban forest to the public and to policymakers. This literature review is an attempt to consolidate all the benefits of the urban forest in one document for those who are interested in or wish to enunciate these benefits.

Background Information

Urbanized metropolitan areas cover approximately 3.5% of the lower 48 states in the United States, with the urban forest consisting of an estimated 3.8 billion trees and covering approximately 33.4 % of the surface area (27.1% in heavily urbanized areas)[5] . Eighty percent of North Americans live in cities and towns, spending 90% of their time indoors or in controlled microclimates[6] , largely separated from the natural world.

Urban forests, via normal metabolic processes, perform ecosystem services for humans valued at many hundreds of billions of dollars in equivalent human-engineered systems. Services otherwise provided by the normal functioning of ecosystems are replaced in cities by human engineers, human capital, and manufactured (built products) such as air conditioning, air filtration, humidifiers, awnings, grocery stores, gutters, storm drains, catch basins, and built landscapes.

The primary environmental issues in the urban environment are air pollution, water pollution, the urban heat island effect, and noise pollution. The primary benefits of urban forests are cooling urban areas, which lowers energy demand and slows atmospheric chemical reactions that precede smog formation. Urban forests absorb gaseous and solid air pollutants. The urban canopy slows rainfall that may otherwise flow across an impermeable surface directly into waterways. Urban forests store carbon and absorb gases. And the urban forest canopy blocks ultraviolet light and slows wind speeds.

Urban forests also signify ‘healthy’ or ‘desirable’ areas, benefiting businesses, homeowners and landlords by inducing a willingness-to-pay on the part of potential customers, raising property values for homeowners, and allowing landlords to charge higher rent in areas with healthy trees and attractive landscaping. Urban forests harbor wildlife and perform other ecosystem services. Greenways may connect urban environments to outside ‘wild’ areas, allowing wildlife - both animals and plants - to move across the landscape.

Physiological processes overview

Trees are living creatures, and as such perform functions, or physiological processes, to maintain life. These functions are generally called ‘metabolism’ here. Most functions important to this paper with respect to urban forest benefits are performed as a result of photosynthesis, respiration and transpiration.

Trees absorb carbon dioxide through their leaves via tiny openings called *stomata*. Water and minerals are taken into the plant through the roots. Plants use photosynthesis to transform the water and absorbed carbon dioxide into oxygen and carbohydrate, which then are used for growth and other life functions. One life function is respiration, which releases energy stored in carbohydrate and in cells for fuel for the plant’s life processes. Lastly, transpiration is the evaporation of water through the plant, mainly through leaves. Transpiration cools the plant and powers the flow of water through the plant.

Trees and shrubs absorb gaseous pollutants through their stomata, filtering urban air. Photosynthesis requires leaves, and leaves shade our cities, which helps lower urban temperatures and blocks harmful rays from the sun. Leaves also moderate wind speeds and intercept rainfall and dry pollutants. Transpiration cools the air near trees through the process of latent heat of evaporation. A major constituent of wood is carbon. Trees help avoid carbon release from fossil fuel burning by moderating microclimates around buildings and therefore lowering energy demands .

Pollution in an urban context

Air pollution

Although there are many species of air pollutants, only a few are currently considered serious enough to human health to be monitored and have formal programs to reduce their concentrations in the atmosphere. The United States Environmental Protection Agency (EPA) has established seven ‘criteria’ air pollutants that are monitored for levels affecting human health as established in National Ambient Air Quality Standards: Carbon Monoxide (CO), lead (Pb), Nitrogen Dioxide (NO_2), low-level ozone (O_3), Particulate Matter (PM_{10} and $PM_{2.5}$) - small particles of soot, dust and other solid pollutants, and Sulfur Dioxide (SO_2).

In addition, many state and local governments target Volatile Organic Compounds (VOCs) for reduction, as many VOCs contribute to the formation of smog and low-level ozone. Examples of common VOCs include benzene, isoprene, methylene chloride, terpenes and toluene.

Carbon Monoxide is formed from the incomplete combustion of fossil fuels. Airborne lead sources include paint, lead battery manufacturing and smelters. Nitrogen Dioxide is formed from fossil fuel combustion primarily from automobiles. Low-level ozone is formed from the reaction of NO_x and VOCs with sunlight and water, generally occurring in temperatures above 70 F. Particulate Matter comes from many sources including agriculture, industry, diesel engines. Sulfur Dioxide comes principally from coal-fired plants and the petrochemical industry. VOCs are formed in automobile engines. Certain industry processes and many trees and shrubs emit small amounts of VOCs into the atmosphere[7] and some species are net emitters of VOCs – that is, they emit more than they absorb or intercept.

Water pollution

There is a wide range of possible water pollutants in the urban environment. Petrochemicals from automobiles, metals from automobile brake linings, heavy metals from certain (older) roofing materials, phosphates and nitrogen from lawn and garden care products and agricultural activities, pet feces, etc. can be washed into receiving waterways by rain and snowmelt.

The urban tree canopy intercepts rainfall and slows the rate of runoff. Slowing this rate allows more precipitation to infiltrate the soil, delaying the time of peak flow and reducing the total amount of overland flow to the receiving waters. A reduction in the total amount of flow reduces the total amount of pollutants washed off of urban surfaces and into receiving waters. Another urban water quality issue concerns combined sewer and storm water systems typical of older city infrastructure. Increased impervious surfaces create greater stormwater runoff and exceed capacity of existing combined systems during peak precipitation events. Typically combined sewer and stormwater overflows bypass treatment and are directly discharged into receiving water bodies.

Urban heat islands

The urban heat island is a phenomenon of greater heat in urban areas than the surrounding rural areas. This is caused by concrete, asphalt, and other hard surfaces in a city absorbing heat during the day and releasing the absorbed heat gradually at night, keeping urban areas warmer than surrounding rural areas. Although each city varies, temperatures can be 6-8 degrees higher in urban areas (see sidebar on page 15). Except in a city's core areas, heat islands are created mainly by an absence of vegetation and by the efficient absorption of solar radiation by urban surfaces such as concrete. Urban surfaces efficiently store sensible heat and the absence of vegetation decreases cooling by evapotranspiration

Elevated temperatures in urban heat islands increase cooling energy use and accelerate the formation of urban smog. As an example of the effects of urban heat islands, analysis of temperature trends for the last 100 years in several large U.S. cities indicate that, since ~1940, temperatures in urban areas have increased by about 0.5–3.0°C. Typically, electricity demand in cities increases by 2–4% for each 1°C increase in temperature. A study estimated that 5–10% of the current urban electricity demand is spent to cool buildings just to compensate for the increased 0.5–3.0°C in urban temperatures.

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Environmental Services of Urban Forests

Ecosystem services are defined as the benefits human populations derive, directly or indirectly, from ecosystem functions[1] . The benefits conferred by the urban forest are numerous and are an important component of ecosystem services in general.   New studies are being completed that show the extent of many urban forests is decreasing, reducing the benefits of urban forest ecosystem services provided to human societies and the planet as a whole.

17 large-scale ecosystem services have been enumerated, from gas regulation, climate regulation and water regulation through genetic resources, recreation and cultural services. See the sidebar for further explanation of ecosystem services[2]. It should be noted that this quantification, which worldwide totaled US $33T in 1997, omitted urban ecosystem functions[3].

A Swedish study[4] identified seven distinct, different possible urban ecosystems that can be called natural, even if almost all areas in cities are manipulated and managed by man: street trees, lawns/parks, urban forests, cultivated land, wetlands, lakes/sea, and streams – the natural green and blue areas within a city. These systems generate a range of ecosystem services, but the authors conceded that street trees are too small to be considered ecosystems in their own right, and should rather be regarded as elements of a larger system. Ecosystem services of the urban forest quantified thus far are outlined below.

Sidebar: Ecosystem Functions[1]

Ecosystem Service	Ecosystem Functions	Examples
-Gas regulation	Regulates atmospheric chemical composition	Ozone for UVB protection, SO_x levels.
-Climate regulation	Regulates climate and weather processes	Greenhouse gas regulation
-Disturbance regulation	Dampens and regulates integrity of ecosystem response to fluctuations	Storm protection, drought recovery
-Water regulation	Regulates hydrological flows	Agricultural water provision
-Water supply	Stores and retains water	Drinking water provision
-Erosion control/sediment retention	Retains soil within an ecosystem	Storage of silt in lakes, topsoil protection
-Soil formation	Soil formation processes	Accumulation of organic material
- Nutrient cycling	Stores, cycles, processes, and acquires nutrients	Nitrogen fixation
-Waste treatment	Recovers, removes, or breaks down excess nutrients or compounds	Waste treatment
-Pollination	Movement of floral gametes	Plant reproduction
-Biological control	Regulates populations	Control of pests, herbivory reduction
-Refugia	Habitat for resident and transient populations	Nurseries, habitat
-Food production	The portion of Gross Primary Production extractable as food	Crop, game production
-Raw materials	The portion of Gross Primary Production extractable as raw materials	Lumber, fuel production
-Genetic resources	Sources of unique biological materials and products	Medicine, genes for resistance
-Recreation	Provides recreational opportunities	Sport fishing, camping
-Cultural ecosystems	Provides cultural opportunities	Aesthetic, spiritual values of

1. Adapted from Costanza et al. 1997.

Air quality improvement

Air pollution comes in two forms important to this paper: solid and gaseous. Examples of solid pollutants (particulate matter) are tiny particles of soot, dust, etc. Gaseous pollutants include ozone and carbon monoxide.

Urban forests improve air quality by intercepting and filtering dry deposition (deposited without precipitation) of airborne particulate matter (generally, NO_x and SO_x)[5]. Urban forests also absorb gaseous pollutants through their leaf stomata. Air pollution absorption rates are affected by local differences in climate, pollutant concentrations, and canopy cover and structure[6]. Due to leaf fall, litter fall, precipitation and wind, interception of pollutants is not permanent[7,8,9]. Conifers are commonly suggested to be good dry deposition interceptors due to their greater surface area and longer period in leaf[10].

The current understanding of the urban atmosphere is that sustaining or increasing urban forest cover will likely help sustain or improve urban air quality, particularly in areas immediately around the area of increased tree cover[11] , due to the ability of leaves to absorb and store airborne pollutants. A study[12] quantified how the Chicago area's urban forest improved air quality and conservatively estimated that overall air quality improvements due to the urban forest were between .3 - 1%, with the greatest effect on PM_{10} and ozone.

Particulate matter

A number of studies have quantified the amount of dry deposition received by canopies. A study in Sacramento, CA, USA estimated that approximately 1,457 metric tons of air pollutants are absorbed annually by Sacramento County's 6 million trees[13]; the average uptake per day was 5.9 tons. Pollutant uptake rates decreased with decreasing tree canopy cover along an urban-to-rural gradient. This study did not include effects from air temperature decrease or Biogenic Volatile Organic Compounds (BVOC) emissions[14]. In 1994, trees in New York City USA removed an estimated 1,821 metric tons of air pollution. Air pollution removal by urban forests in Atlanta, GA USA was 1,196 tons, and Baltimore, MD, USA's urban forests removed 499 tons. Pollution removal per m^2 of canopy cover was fairly similar among these cities (New York: 13.7g/m^2/yr; Baltimore: 12.2 g/m^2/yr; Atlanta: 10.6 g/m^2/yr.)[15] Another study[16] quantified the air quality benefits derived from the urban forest of Brooklyn, NY, USA and found Brooklyn's trees remove about 2,500 tons of carbon per year and about 254 metric tons of air pollution per year. In 1991, an estimated 6,145 tons of air pollutants was removed by Chicago, IL, USA's urban forest[17]. The basis for many of the quantifications of the ability of trees to remove air pollution from their surroundings is based on the works of Arthur Winer and colleagues.

Urban forests can also indirectly affect air quality by avoiding hydrocarbon release – decreased energy demands result in lower hydrocarbon particulate emissions[18,19] . Lower temperatures as a result of the urban forest canopy can decrease reaction rates of chemical processes relating to smog. Included among these processes are lower emissions of mono- and isoterpenes - chemical precursors to smog formation - and lower reaction rates of these and other photochemical reactions that contribute to smog and ozone formation[20].

Ozone and smog

Low-level ozone (as opposed to ultraviolet-blocking stratospheric ozone) is a serious air pollutant in urban areas, hypothesized to exacerbate health issues, particularly asthma[21] (see sidebar for more information). Woody vegetation and urban forests in general can positively improve ozone levels through a number of mechanisms, but a few species can negatively contribute to ozone levels by emitting ozone precursors (BVOCs) such as monoterpenes and isoprenes. Photochemical smog also changes the albedo of the immediate area, generally increasing the albedo[22].

A large study[23] modeling the effects of increased urban tree cover on ozone concentrations from Washington, DC, USA to central Massachusetts found that urban trees generally reduce ozone concentrations in cities, but tend to increase average ozone concentrations in the larger region. The study found average ozone reductions in urban areas (1 ppb) during daylight were greater than the average ozone increase (0.26 ppb) for the modeled area. Increasing urban tree cover from 20 to 40% led to an average decrease in hourly ozone concentrations in urban areas during daylight hours of 1 ppb (2.4%) with a peak decrease of 2.4 ppb (4.1%). However, nighttime (20:00–1:00 EST) ozone concentrations increased due to reduced wind speeds and loss of NO_x scavenging of ozone from increased deposition of NO_x.; that is, trees emit BVOCs, but their ability to decrease temperatures during daylight hours generally outweighs the BVOC emissions. Changes in the tree species composition in the model had no noticeable change on ozone concentrations. Overall, 8-hour average ozone concentration in urban areas dropped by 0.5 ppb (1%) throughout the day. The study noted that increasing urban tree cover is a viable strategy to help cities in non-attainment areas, but slight overall increases in ozone concentrations may occur . Another study[24] confirmed that biogenic sources make important contributions to VOC and NO_x emissions in parts of eastern North America and southern Europe.

Species composition is important when considering whether a single tree, woody plant or urban forest as a whole is a net emitter of BVOCs[25]. For example, California, USA has measured emissions for many taxa[26, 27, 28] . Low BVOC emitters can be found in the families Aceraceae, Anacardiaceae, Bignoniaceae, Caprifoliaceae, Compositae, Cupressaceae, Cycadaceae, Ericaceae, Juglandaceae, Magnoliaceae, Oleaceae, Rhamnaceae, Rosaceae, Sapindaceae, and Taxodiaceae. Medium or high BVOC emitters include the Fagaceae, Myrtacae and Platanacae families, while Leguminosae had widely varying emissions[29]. Although some tree species are net emitters of BVOCs, the urban forest canopy as a whole has far greater value in being large deposition surfaces for gaseous pollutants. This fact alone far outweighs their ozone-forming potential as BVOC emitters[30].

Sidebar: Low-Level Ozone Formation and Regulation[1]

Ozone is produced in the lower atmosphere by the photochemical reaction of certain Volatile Organic Compounds (glossary) and NO_x. Ozone is a primary constituent of smog. The health effects of low-level ozone include breathing problems, reduced lung function, asthma, irritated eyes, stuffy nose, reduced resistance to colds and other infections, and it may speed up aging of lung tissue. Exposure to ambient ozone concentrations has been linked to increased hospital admissions for respiratory aliments such as asthma. Some environmental effects include damaged plants, and smog formed from ozone can cause reduced visibility. Low-level ozone also damages materials such as rubber and some fabrics.

The United States Environmental Protection Agency (EPA) created new National Ambient Air Quality Standards (NAAQS) for low-level ozone in 1997.

Concentrations are determined in one-hour and eight-hour volumetric averages. One-hour averages have been phased out but will continue to be monitored to ensure a smooth transition to the new standards created in 1997; some areas may continue to be out of compliance and thus report one-hour concentrations in addition to eight-hour concentrations.

The eight-hour concentration standard is 0.08 parts per million (ppm) and is defined as the 3-year average of the annual 4th-highest daily maximum 8-hour ozone concentrations. This concentration is expected, according to the EPA, to protect human health and vegetation.

1. Adapted from the EPA's Revised Ozone Standard, on-line at: http://www.epa.gov/ttn/oarpg/naaqsfin/o3fact.html

Heat island mitigation

The urban heat island is a phenomenon of greater heat in urban areas than the surrounding rural areas. This is caused by concrete, asphalt, and other hard impervious surfaces in a city absorbing heat during the day and releasing the absorbed heat gradually at night, keeping urban areas warmer than surrounding rural areas. Although each city varies, temperatures can be 6-8 degrees C (higher in urban areas (see sidebar). Except in a city's core areas, heat islands are created mainly by an absence of vegetation and by the efficient absorption of solar radiation by urban surfaces such as concrete. Urban surfaces efficiently store sensible heat and the absence of vegetation decreases cooling by evapotranspiration.

Elevated temperatures in urban heat islands increase cooling energy use and accelerate the formation of urban smog. In the earth's temperate zones, approximately 1.2 MWh of solar energy falls annually on each m^2 surface, equivalent to 250 kg of brown coal a year[31].

Much work needs to be done to precisely quantify the magnitude and extent of urban heat islands. While some progress has been made, much thermal description of urban areas has been slow to advance beyond qualitative description of thermal patterns and simple correlations, according to one researcher[32] , whereas a recent paper on urban heat islands[33] asserts that there has been considerable advancement in the understanding of urban climatology in the last 15 years.

As an example of the effects of urban heat islands, analysis of temperature trends for the last 100 years in several large U.S. cities indicate that, since about 1940, temperatures in urban areas have increased by about 0.5–3.0°C[34]. Typically, electricity demand in cities increases by 2–4% for each 1°C increase in temperature A study estimated that 5–10% of the current urban electricity demand is spent to cool buildings just to compensate for the increased 0.5–3.0°C in urban areas[35]. A study in Athens, Greece found the mean heat island intensity exceeds 10°C, the cooling load of urban buildings may be doubled, the peak electricity load for cooling purposes may be tripled especially for higher set point temperatures, while the minimum performance value of air conditioners may be decreased up to 25% because of the higher ambient temperatures[36].

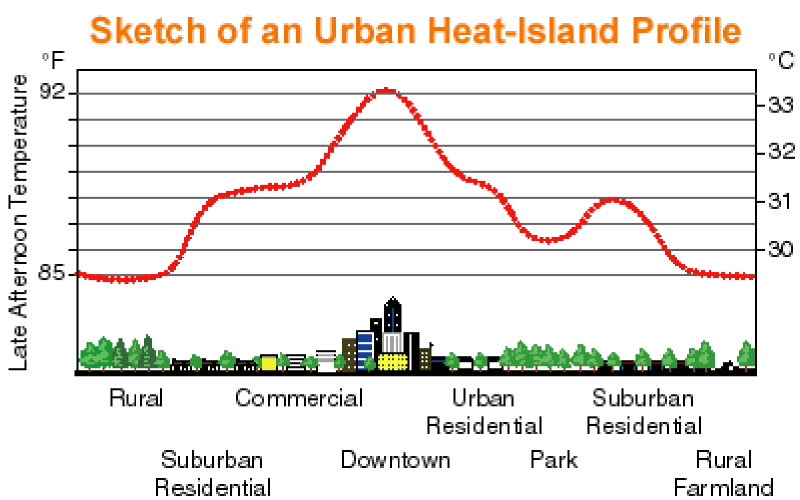
The urban forest canopy can do much to reduce the effects of the urban heat island, and greenspace provides a significant flux of water and latent heat into the urban boundary layer[37]. Land-use patterns determine the amount of sunlight – and therefore heat – an area receives[38]. Canopy coverage is the main determinant of temperature reduction[39]- the more tree canopy covering an area, the less sunlight is absorbed by hard surfaces and later re-radiated back into the urban atmosphere.

Trees and vegetation reduce the temperature of cities by shading (by reducing sensible heat) and evapotranspiration (by latent heat of evaporation), although trees can contribute slightly to the urban heat island effect by reducing wind speeds[40]. A single tree with a $10m^2$ canopy transpiring about 400 l of water a day for 12 hours has an average cooling efficiency of 23 kW during 1 day[41]. These vegetation-reduced temperatures lessen energy demands and lessen stress on the electrical grid, in addition to lessening the heat stress on vegetation. Extensive vegetative canopy cover also moderates diurnal temperature swings[42]. A study[43] found that the urban forest of Sacramento reduced the city's cooling requirement by 12%. The cooling effects of vegetation can be felt at considerable distances from the vegetation. One study found noticeably cooler temperatures 100m from a small park, with an average temperature difference of 2 degrees K at 20m from small wooded parks, and .5 degrees K at 80m from the sites studied; the average temperature difference within the sites was 2.8 degrees K[44]. Another study of a large park in Mexico City found that the park (about 500 ha) was 2–3 °C cooler with respect to its boundaries and its influence reaches a distance about the same as its width (2 km)[45] . Forest belts surrounding Stuttgart, Germany, contribute to the cooling of the central city. Thermals draw in cooler air from the periphery and cool downtown areas[46].

A study of sprawl in Atlanta, GA, USA[47], which measured variables including canopy cover and lawn area, found that residential lot size in the area contributed to the 'thermal footprint' of the region. Low-density, large lot-sized developments generally have a lower fraction of the parcel covered by tree canopy, thereby emitting more excess radiant solar energy per parcel than an area that is more densely urbanized and having a higher fraction of the parcel covered by tree canopy. In the study area, there was increased incident solar radiation absorbed by hard surfaces and lawns because the developments preferred landscaping with large, open lawns at the expense of tree canopy.

Lower temperatures as a result of the urban forest canopy can decrease reaction rates of chemical processes relating to smog. Included among these processes are lower emissions of mono- and isoterpenes, which are chemical precursors to smog formation, and lower reaction rates of these and other photochemical reactions that contribute to smog formation[48,49]. Lower urban air temperatures also reduce the release of hydrocarbons from anthropogenic and biogenic sources[50].. For example, when cars are parked in the shade of trees in parking lots, the lower temperatures reduce VOC evaporation from the fuel system[51].

Sidebar: Idealized Urban Heat Island Profile[1]



1. From the Lawrence Berkeley Laboratory Heat Island Group, on-line at: http://eetd.lbl.gov/HeatIsland/HighTemps/

Carbon sequestration and reduction

Urban forests reduce atmospheric carbon dioxide (CO_2) by the uptake of Carbon Monoxide (CO) through their leaves (which is greater than CO release from metabolism), provided that the plant is actively growing. This uptake varies greatly between species, climate and age of the plant. In addition, urban forests reduce atmospheric CO_2 by saving energy spent on cooling and heating buildings – energy produced via the consumption of carbon-based fossil fuels[52]. In winter, the slower wind speeds caused by the plant reduces the amount of heat carried away by the moving air, thus lowering energy costs.

A recent analysis for Baton Rouge, LA, USA, Sacramento, CA, USA and Salt Lake City, UT, USA estimated that planting an average of four shade trees per house (each with a top view cross section of 50 m^2) would lead to an annual reduction in carbon emissions from power plants of 16,000, 41,000, and 9000 t, respectively. The per-tree reduction in carbon emissions was about 10–11 kg per year. These reductions only account for the direct reduction in the net cooling- and heating-energy use of buildings. The study found once the impact of the community cooling is included, these savings are increased by at least 25%[53]. This study expanded on earlier work that found a single tree planted in Los Angeles avoids the combustion of 18 kg of carbon annually, even though it sequesters only 4.5–11 kg. A 4-city study estimated a 92 kiloton reduction per year in carbon emissions simply by siting 4 shade trees around houses in those cities[54].

A study[55] estimated the amount of carbon stored in the area around a medium-sized city (Sacramento, CA, USA) and found the urban forest stored 8 million tons of CO_2 (31 t/ha). Energy savings further reduced CO_2 emissions by 75,600 tons, and the reduction of CO_2 by the urban forest offset the total CO_2 emitted by human consumption by 1.8%. Another study estimated the amount of sequestration by urban trees in the coterminous United States[56] and found total current storage at 700 million tons of carbon, a gross carbon sequestration rate of 22.8 million tC/yr, and the national average urban forest carbon storage density is 25.1 tC/ha, compared with 53.5 tC/ha in forest stands. A modeling study[57] simulated a mass tree-planting of 100 million trees. The estimated total carbon stored and avoided by the trees after 50 years was 363 million tC, which is <1% of the estimated amount of carbon emitted in the USA over the same 50-year period. Increasing passenger automobiles' fuel efficiency by 0.5 km/l over 50 years would also produce the same carbon effects as the 100 million trees.

Hydrology

The urban forest canopy intercepts and absorbs precipitation, slowing runoff and increasing infiltration, although timing and intensity of precipitation are important factors when considering the efficacy of the canopy in performing these functions. In addition, urban forests remove water from the soil by evapotranspiration, allowing additional precipitation to infiltrate – although evapotranspiration may be reduced over certain urban reflective surfaces[58] such as mulch and concrete .

In general, the urban forest canopy can intercept a substantial amount of precipitation[59,60,61,62] As grey infrastructure replaces green infrastructure, the urban forest's ability to slow and detain stormwater lessens. For example, Philadelphia's lost canopy now requires replacement of the stormwater containment at a cost of US$105M[63]. Interception of precipitation varies by tree species, leaf type, and size of canopy[64]. A few studies have quantified or modeled rainfall interception. For example, in coastal southern California a typical medium-sized tree was estimated to intercept 2,380 gallons annually[65] , whereas in inland California each street and park tree was estimated to intercept 845 gallons annually[66].

Polluted runoff

Land cover influences the amount of pollutants such as nitrogen and phosphorus in runoff that flows to receiving waters, and generally the amount of such pollutants increases as the amount of agriculture or urban land increases in a watershed[67]. However, the relative impacts of different types of land use (such as residential, commercial, industrial) on the receiving waters have yet to be definitively ascertained and quantified[68] .

Waterways and lakes in and near cities areas can be polluted by soil erosion and water runoff that contains fertilizers and pesticides from landscaped lawns and trees, oil, and raw sewage (eutrophication). Trees and vegetation can help ameliorate water quality problems in communities by reducing storm-water runoff and soil erosion, given adequate canopy coverage. One study estimated that forests in the United States are worth at least $400 B in stormwater management[69].

Communities are beginning to understand the necessity for controlling stormwater runoff. A preliminary study in Nashville, TN, USA[70] found significant levels of bacterial contamination in runoff from lawns and streets, the source hypothesized as being from human pets. Communities are affected by federal mandates as well – for example, a federal directive is affecting Southeastern Michigan, USA and is requiring communities there to reduce the amount of stormwater runoff into rivers and streams[71] - with the municipalities responsible for funding and enforcement.

Rate and volume of runoff

In many communities, the rate and volume of stormwater runoff have increased beyond the capacity of existing storm-water drainage systems. This is caused by continued development of impermeable surfaces (such as roads and parking lots) that cannot absorb water, changing natural drainage patterns and loss of vegetation. Increasing the area of impervious surfaces also reduces the amount of natural absorption of water by soil. Permeable pavement can significantly reduce runoff and eutrophic loads[72], and wetlands are effective at reducing runoff and flooding, and many communities are restoring old wetlands or creating new wetlands for flood control purposes[73] .

Urban forests do not uniformly slow stormwater runoff. Street trees avoid the greatest amount of runoff, as the majority of street tree canopies project over a paved surface, as opposed to a private or park tree in the middle of a lawn[74] . While estimates vary[75,76,77] , it is generally conceded that increasing urban forest canopy cover decreases runoff and eases pressure on stormwater systems. For example, estimates indicate that Salt Lake City's tree cover reduces the runoff produced by a 12-hour storm with an inch of rain by 17%[78] . However, a team with an interception model concludes that urban forests are likely to produce more benefits through water quality protection than through flood control[79], mainly due to the fact that many deciduous trees in the western United States are out of leaf during most storm events, as most precipitation falls during the winter months. A study of watersheds in the southeastern USA[80] compared an urbanized watershed and a forested watershed, and found that despite similar rainfall regimes and smaller size, the urban watershed had 72% greater annual streamflow volume, 66% greater sediment load, and greater nutrient loads. In Forest Park, GA, USA, the average tree canopy density declined from 22% in 1974 to 17% in 1996, resulting in a 28% increase in runoff, which would require a stormwater system equivalent in value to a $4.5 million system (the stormwater retention capacity was reduced from $15.8 million in 1974 to $11.3 million in 1996)[81].

Non-point source urban runoff generally is a substantial source of pollutants to the waters receiving the runoff[82]. Peak flows are generally higher due to the amount of impervious surface preventing infiltration. In vegetated areas only 5–15% of the rainwater runs off the ground, with the rest evaporating or infiltrating the ground. In vegetation-free cities about 60% of the rain water runs off through stormwater drains[83] , with most of the remainder infiltrating into the ground. . Metals can also be present in urban runoff, roofs and automobile brakes being major sources. One recent study[84] found asphalt shingles as a possible source for lead in urban water bodies. Sediment loads in urban areas may be higher as well, all contributing to occasional oxygen deficit and higher nutrient loads[85,86]. Quantifying issues surrounding urban discharges is complex, due to the many paths a raindrop can take from roof to receiving waters in an urban environment, and understanding urban discharge's effects on water quality and benthic communities is currently problematic at best[87] .

Soil erosion and sedimentation

Trees can limit soil erosion by helping control storm-water flow. Fibrous root systems hold soil in place so that it is not washed away by rain or flowing water[88]. Erosion can be especially severe at construction sites in urban areas. Research has found that while forested land can lose about 50 tons of soil per square mile per year, developing areas can lose 25,000 to 50,000 tons[89]. Urbanization increases sedimentation as discharges of stormwater are greater due to increased impervious surface: parking lots, buildings, streets, even lawns. This increased discharge increases the rate of channel erosion[90] and turbidity of streams in urban areas.

Noise abatement

Noise from traffic and other sources decreases the quality of life in urban areas. The overall costs of noise have been estimated to be in the range of 0.2 –2% of GDP in the EU[91]. Reducing noise and stress in the urban environment increases the quality of life. Sound scattering by vegetation is complicated and depends upon a number of factors, including biomass distribution, plant spacing, plant height, leaf size and shape, and the acoustic impedance of the plant material[92]. The majority of the recent research efforts have been centered on two categories: the study of vegetative barriers as <u>measurable</u> road noise attenuators, and the investigation of the psychological or <u>perceived effectiveness</u> of vegetative barriers. The two fields are necessary because in order to be an effective attenuator ('buffer'), plantings must be of sufficient width, generally over 10m (~34 ft.) wide[93] to reduce volume approximately 3-8 dBA.

One study[94] has quantified type and height of vegetation to actually attenuate noise. Density, height, length and width of tree belts are the most effective factors in reducing noise rather than leaf size and branching characteristics. Noise diffusion is obtained via density, height, length and width, and noise absorption is obtained via leaf size and branching characteristics. Diffusion was best at reducing noise, and the higher the density of vegetation, and the more foliage and branches to reduce sound energy, the greater the scattering effect. Width of vegetation belts is the other significant noise reduction factor. Implicit in this assessment is the presence of evergreen understory vegetation to provide year-round attenuation.

In qualitative studies[95] the psychological effects of vegetative barriers to roadway noise attenuation was considered. The researchers found that vegetative barriers created a perceived attenuation of road noise of 3 to 5 dBA. The conclusions were visualization of the noise source directly affected the perceived sound levels such that when portions of a test vegetative barrier were removed, listeners perceived the levels increased disproportionately. Nevertheless, the Federal Highway Administration recommends vegetative barriers as both a physical and psychological component of noise attenuation strategies[96] and states that a 200-foot width of vegetation can cut the loudness of traffic noise in half (10 dBA).

Sidebar: Decibels and Human Hearing[1]

Weakest sound heard	0dB
Normal conversation (3-5')	60-70dB
Telephone dial tone	80dB
City Traffic (inside car)	85dB
Subway train at 200'	95dB
Hearing loss (sustained exposure)	90-95dB
Power mower	107dB
Power saw	110dB
Pain begins	125dB
Jet engine at 100'	140dB
Death of hearing tissue	180dB

<u>Perceptions of Increases in Decibel Level</u>

Imperceptible Change	1dB
Barely Perceptible Change	3dB
Clearly Noticeable Change	5dB
About Twice as Loud	10dB
About Four Times as Loud	20dB

1. Adapted from the Decibel (Loudness) Comparison Chart on-line at: http://www.gcaudio.com/resources/howtos/loudness.html

Habitat and wildlife corridors

Urban areas disconnect or fragment natural areas, impeding animal and plant movement. Land-use planners and designers create urban habitats variously called greenspace, wedges, open space, woodlots, corridors, fingers, or greenways. Efficiency and utility of land-use theories, and landscape design and practices will not be reviewed here; rather, urban places as wildlife habitats and their spatial distribution will be presented.

Urban metropolitan areas cover approximately 3.5% of the land in the lower 48 states in the United States, with the urban forest consisting of an estimated 3.8 billion trees covering approximately 33.4 % of the surface area (less - 27.1% - in heavily urbanized areas)[97]. The loss of natural areas due to human population expansion, decreasing size of parcel ownership[98], and intensive agriculture is resulting in an increased interest in the urban forest as habitat, as human population growth and urban development are having environmental impacts in areas far from urban centers[99] , including loss of primary productivity and concurrent rise in CO_2 emissions from human development[100]. Urban forests, despite frequent disturbance and high stress, harbor wildlife (sometimes purportedly increasing biodiversity[101]) and can serve as corridors between fragmented habitat patches; cities themselves can have a variety of habitats and can be rich in plant and animal species[102].

Wildlife in urban areas reflects the available habitat and indicates the health and condition of the urban environment. Generally, areas of highest biodiversity in cities are in areas of highest socioeconomic status[103]; a study in the northern hardwood forest region[104] found, however, that canopy cover decreased as human population increased.

The urban forest in many cities is dominated by few tree species, many well-adapted to their site[105,106,107] . Recommendations for stability of urban forest populations depend upon climate and other factors[108] , and one of the functions of the urban forester is to ensure forest stability. A stable canopy ensures stable habitat - however there is no single prescription for canopy stability. Many different tools are required to assess habitat suitability and quality in urban environments; whereas some studies indicate highest diversity occurs in built environments[109], others[110] indicate highest diversity at the urban-rural fringe. Studies[111],[112],[113] indicate that landscape design and management play stronger roles in habitat quality and species diversity than land-use type.

Riparian networks are the backbone of urban habitats, and especially of habitat corridors[114,115] and usually are expected to be the richest remaining natural areas for species richness and species diversity[116] . The paucity of empirical studies determining the effectiveness of corridors (due to complexity and area) was addressed by a large-scale study[117] that determined corridors are indeed beneficial and their influence extends beyond their added area. The study demonstrated that corridors provide benefits in excess of the associated increase in habitat area, and that corridors facilitate movement between patches and maintain key mutualisms between plants and animals.

Whether fragmented habitats are adequate for species survival is an ongoing debate[118,119,120];. Nevertheless, the urban habitat supports a rich assemblage of both plant and animal species[121,122,123,124], both relict and invasive, despite the challenges of frequent disturbance and fragmentation. As our understanding of the importance of biodiversity improves, the urban forest as habitat will likely increase in importance[125],[126].

Summary

Urban forests worldwide, via normal metabolic processes, perform ecosystem services for humans valued at billions of dollars in equivalent engineered systems. The urban forest in even a small town may filter tons of airborne particulate matter pollution. Street trees slow stormwater runoff because much of their canopies are over impervious surfaces. The forest as a whole lowers urban temperatures, which lowers human energy consumption, slows down reaction rates of atmospheric chemicals leading to smog formation, and moderates the microclimate for human comfort. The urban forest canopy supports a diverse array of wildlife, both as a habitat in itself and as a corridor between patches. And, as a component of the urban forest, woody plants can attenuate noise if planted correctly.

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Public Health Benefits of the Urban Forest

The built environment appears to affect human health and well-being[1] . Although the literature is replete with papers containing theories of how conceptual frameworks of built environments, trees, greenery and open space affect human health, safety and well being, few empirical studies have been performed to prove these associations or that causation even exists.

The built environment

The built environment consists of not only human-built objects – buildings, streets, sewers, etc., but also living things in the built space as well. Human-built objects are generally called 'gray infrastructure' and living things (and their support) are generally called 'green infrastructure'. Urban forests, as the 'green infrastructure' part of the urban built environment, contribute to the overall public health of cities.

There are strong public-health arguments for the incorporation of greenery, natural light, and visual and physical access to open space in homes and other buildings[2]. In a list of the 10 most important American public health challenges for the new century, then Director of the U.S. Centers for Disease Control, Jeffrey Koplan MD, included at least four challenges that are significantly linked to land-use and urban design issues[3]: integrating physical activity into our daily lives, improving and protecting the environment, recognizing the contributions of mental health to overall health and well-being, and reducing the toll of violence in society.

Historically, cities in the developed world are far healthier places to live now than they have ever been[4] and life expectancy in the developed world is at an all-time high. Improved hygiene, access to health care, and regulatory action are the major factors for this improvement. Improving quality of life in cities is the major focus of environmental health programs. Contrast this with epidemiological studies[5] showing that, absent consideration of socio-economic divisions, public health in the more-developed countries is no longer primarily determined by environmental factors. Life-style and social choices are now the significant causes of avoidable health loss. Cardiovascular disease, cancer, depression and road accidents account for more than twice the burden of disease than environmental factors such as acute respiratory infections, diarrhea, etc.[6] . Air pollution is the most significant cause of health problems due to environmental causes in the cities of the developed world. The public health community[7] recommends further research to determine the effect of the built environment on air quality impacts that increasing numbers of automobiles in use in a community have on its air quality.

Sidebar: **Surgeon General's 10 Health Challenges**

1. Institute a Rational Health Care System
2. Eliminate Health Disparities
3. Focus on Children's Emotional and Intellectual Development
4. Achieve a Longer "Healthspan"
5. Integrate Physical Activity and Healthy Eating Into Daily Lives
6. Clean Up and Protect the Environment
7. Prepare to Respond to Emerging Infectious Diseases
8. Recognize and Address the Contributions of Mental Health to Overall Health and Well-being
9. Reduce the Toll of Violence in Society
10. Use New Scientific Knowledge and Technological Advances Wisely

Generally, descriptions of environments and human health effects exist in modeled concepts and frameworks. A recently published literature review[8] attempted to identify various concepts in the literature concerning environmental quality, the relationships between these various concepts, and the bases for these concepts. It reviewed the main (types of) concepts of livability, environmental quality, quality of life and sustainability. The review found tools were lacking to assess the current and future quality of the urban environment and the implications of spatial and urban planning policies with respect to these qualities. The difficulty may lie in the fact that 'quality' is subjective and the range of perceptions of the urban environment have not been sufficiently quantified.

Evidence is more robust regarding the effects of the *atmosphere* in the built environment on human health. Cities with poor air quality affect the health of their residents. Ongoing epidemiological research has shown that there is a direct relationship between poor air quality and a decline in overall human health[9] .

Journals are filled with hundreds of reports from all over the world that show short- and long-term exposures to current levels of particulate matter and ozone affect death rates, hospitalizations, medical visits, complications of asthma and bronchitis, and other health indicators[10]. Recent studies found that a daily increase of 20 g/m^3 in particulate matter of 10 micron diameter (PM_{10}) increases the death rate by about 1%[11], and that a 25 g/m^3 increase in lifetime average concentration of particulate matter of 2.5 micron diameter ($PM_{2.5}$) in a city increases the overall total annual death rate by some 15%[12], and another study[13] attempted to analyze the correlation of air pollution to cardiopulmonary cause of premature death, and estimated that in the United States approximately 64,000 premature deaths may occur each year due to air pollution. The way the built environment is designed is believed to contribute to the issues above, and recently a large-scale research agenda was formulated to study the relationship to the built environment and public health[14] .

Asthma

Asthma is a chronic, inflammatory lung disease characterized by recurrent breathing problems, usually triggered by allergens, infection, exercise, cold air, and other factors may also be triggers[15]. Costs to individuals with asthma average over US$4,900.00 annually[16] and in 1998, the estimated 17 million asthma sufferers in the United States accounted for an estimated 12.7 billion dollars annually[17] . Asthma prevalence is increasing in the United States[18,19] and remains one of a few diseases in the United States that is increasing in incidence in both children and adults. It is believed certain chronic diseases such as asthma are exacerbated by effects of the built environment. High levels of outdoor air pollution have been associated with short-term increases in asthma morbidity and mortality[20] . However, there is no robust consensus on definitive causative factors for asthma attacks, nor is there agreement on environmental treatments for asthma, although many studies exist that show an association between particulate air pollution and negative respiratory health, especially among children[21,22,23,24] and the elderly[25] with asthmatic symptoms. Trees absorb particulate matter, making a net positive contribution to air quality (further detailed in the Environmental Services section).

Asthma is frequently cited as being an unintended side effect of widespread automobile usage. In the past 50 years, the number of cars and trucks in the United States has more than quadrupled while the US population has less than doubled. The average total annual mileage driven by Americans in 1970 was 4,587 miles per year. In 1995 it was 9,567 miles per year – more than twice as much[26] . Most of this travel occurs in personal automobiles. In many communities, non-motorized modes of transportation and the needed infrastructure to support these modes may be unavailable or, given an average trip length of nearly 9 miles, walking and biking options are, in many cases, not an easy choice to make[27]. The 1996 Atlanta Olympic Games is frequently cited as illustrating the automobile-asthma link. During the games, driving decreased 22.5% as cars were restricted in the downtown area, and at the same time, emergency room and hospital admissions for asthma decreased 41.6%, while the occurrence of other medical events was unchanged[28] . The urban forests' ability to absorb airborne gaseous and solid pollutants has been well-modeled; however, how this relates to public health is an important research topic that has only now just begun to be quantified. There is a pressing need for research into the relationship between trees, tree cover, and human health.

General consensus exists that there is an association between vegetation and exacerbation or onset of asthma by exposure to wind-pollinated plants such as grasses, conifer trees, and certain deciduous trees (the common species alder, poplar, cottonwood, birch, oak, ash, plane and sycamore for example); heavily-scented plants, and plants in the daisy family. Indirect causative factors (harboring of dust, mold and pollen) for asthma onset or exacerbation can be found in lawns, hedges and weeds[29] where these plants either retain moisture (creating a condition conducive to mold growth) or decrease wind speeds so as to retain dust and pollen.

Allergies

Allergies are an exaggerated response to a substance or condition produced by the release of histamine or histamine-like substances in affected cells[30] . As with asthma, wind-pollinated trees and plants are major allergen sources[31] , although tree pollen of any kind may be an allergen. Pollen release in trees and shrubs usually is a short-term, seasonal condition, over short distances – the vast majority of pollen from a typical tree falls to the ground in the immediate vicinity of the tree[32] , but windy days may blow pollen many hundreds of feet from the tree. Many wind-pollinated trees are early-flowering and rain may be another mechanism of release by aborting the germination of pollen and releasing fine particles into the air[33] . Trees with fine hairs on leaves or petioles (for example, plane and sycamore) may cause allergic reactions in some people.

Table 1. A list of common landscape trees of the United States having identified allergens, by common name[34,35] :

Acacia
Alder
Ash
Beech
Birch
Box Elder
Cottonwood
Elm
Eucalyptus
Hazel
Hickory
Horse Chestnut
Lime/Linden
London plane/Planetree
Maple
Mesquite
Oak
Olive
Pecan
Pine

Privet

Spruce

Stone fruits: genus *Malus, Prunus*

Sycamore

Tree of Heaven

Walnut

White Mulberry

Willow

Obesity and Type II diabetes

Obesity is defined as having a high amount of body fat, either 30% over ideal weight or having a body mass index (BMI) of 30 kg/m^2 or greater[36] . Americans' obesity rates are increasing rapidly[37] . Over an estimated 15 million adults in the United States have diabetes - 8% of men and women aged 20 years or older[38]. Obesity appears to lessen life expectancy markedly, especially among younger adults[39] , and this continuing trend in obesity is a critical public health threat in the United States[40] . Annual estimates of deaths attributable to obesity in the United States are generally estimated to be between 280,000-325,000[41] , however these figures have recently come under scrutiny[42]. Although estimates for the health care costs of obesity to American society differ, for example a study[43] that took increased mortality into account placed a maximum limit of costs at 4.32%, and another study[44] quoted estimates of direct costs of obesity and physical inactivity accounting for approximately 9.4% of the national health care expenditures in the United States.

Lack of physical activity appears to be related to obesity and type II diabetes[45] . The surgeon general of the United States recommends physical activity to help combat weight issues[46] . The medical literature is full of recommendations for changes in the community environment to promote physical activity, which may offer a practical approach to prevent obesity and its related health issues, and restoration of physical activity as part of the daily routine represents a critical public health goal[47] . Empirical studies are lacking, however, describing methodologies or systems to best categorize which built environments promote physical activity across socioeconomic classes. The only clear results seem to be in research that shows properly designed walkways through a mixed-use, human-scaled urban environment increases pedestrian activity (cf.[48,49]) by creating a feeling of safety and creating interest along the route (such as varied streetscapes, interesting vegetation and gardens).

Trees are a component of open spaces or the paths leading to open spaces and as such can make open spaces more pleasant.

UV Radiation

Excess exposure to ultraviolet radiation (UV) from the sun, especially ultraviolet B (UVB), has been indicated as a factor for adverse effects on human health, including skin cancers and cataracts[50] . More than 1 million cases of skin cancer - either basal, squamous or melanoma - are expected to occur in the United States in the year 2003[51] . Epidemiologists suggest that human's routine exposure to UV in urban areas can result in harmful health effects, particularly for young children. The recovery of the ozone layer – the layer of the stratosphere that protects the surface of the planet from the sun's UV - is not expected to occur until the middle of the 21st century[52] .

Urban trees reduce ultraviolet irradiance in their shade when they obscure both the sun and sky - that is, when there is dense shade. Where trees or other structures obscure only the sun, leaving much of the sky in view, UVB irradiance is greater than suggested by the visible shade. A recent study[53] developed a method to estimate the amount of protection tree canopies can provide to intercept UVB radiation: considering the amount of sky seen through the canopy. In the latitudes between 15-60 degrees, under a tree canopy providing 50% coverage of the sky, UVB protection approximately doubles (an Ultraviolet Protection Factor of 2), and with 90% canopy coverage, UVB protection is 10 times greater (a UPF of 10). The paper recommends improvements in the built environment to include more tree canopy coverage, as many elements of the built environments in urban areas are lacking trees, such as parking lots, commercial centers, and large multifamily units.

Summary

The built environment is a significant factor in the lives of most Americans and for a significant fraction of humanity. We are just now becoming fully aware of the public health consequences of past practices. Although space limitations prevent a thorough discussion of the built environment and green infrastructure, current research indicates that improvements in the built environment are needed to improve the physical health of some populations, and to improve the well-being of many more. Trees are an important component of green infrastructure - the addition of which may prove to be a vital link in improving the well-being of urban residents.

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Psychosocial and Wellness Benefits of Urban Forests

Certainly urban foresters believe that urban and community forests are windows into the souls of our cities[1]. Although there is an increasing volume of empirical social science work regarding the effects of green spaces and nature on the well-being of humans, a review encompassing two issues of an urban planning journal[2] found that no coherent system has been developed to evaluate aspects of and trends in environmental quality in relation to human well-being. The absence of a generally accepted framework for quality of life research is acknowledged as an obstacle to progress to definitively understand if there is an association between exposure to urban forests and some sort of human psychosocial outcome.

Anthropological and psychological evidence suggests that humans have a primal need to connect with nature. Harvard biologist Edward O. Wilson calls this the "biophilia hypothesis", where the human need to associate with the natural world goes beyond attraction or appreciation of nature's aesthetic or utilitarian values. We humans 'know' we are inextricably linked with nature, and as we evolved in close association with nature we developed an unshakable, biologically based emotional dependence on the living world. Later authors have expanded this concept to suggest that humans have an innate bond with nature more generally, implying that certain kinds of contact with the natural world may benefit humans[3] .

The literature is replete with studies that show people prefer a natural environment, one with green places over gray places. Studies show urban dwellers prefer green spaces as well. With regard to urban forests, studies[4,5] show city streets that are lined with trees are viewed more favorably than streets without trees. And, as is seen in another section of this literature review[6] , this preference for trees is most obvious when one considers that residential property values are higher when the property has healthy trees or is located near a park or open space. Preliminary studies show urban areas with the higher income are those with greater tree cover[7] and greatest biodiversity[8] , presumably due to greater resource availability and preferential choice.

Many urban and community foresters report dramatic social impacts from greening cities and towns[9] , either from tree-planting programs, activities in open-space areas, or public gardens. The effects of greening are usually measured as a result of passive or active experience in urban vegetation. Passive experiences include viewing and active experiences include walking or other forms of active recreation. The resultant effects of the urban forest on human healing, relief from stress, perceptions of safety, a sense of accomplishment, or a sense of social or community belonging are reviewed in this section.

Human healing

A few robust studies exist that find a direct connection between shorter hospital stays/shorter healing times and views of green spaces or nature[10,11,12] .The groundbreaking study that is often cited[13] found individual hospital patients with a window looking out on trees (as opposed to a brick wall) had shorter postoperative stays, fewer negative evaluative comments from nurses, and took fewer pain medications. An empirical study of prisoners in Michigan[14] found a connection between reduced sickness and cells having views of nature. Half the prisoners occupied cells along the outside wall, with a window view of rolling farmland and trees, while the other half occupied cells that faced the prison courtyard. Assignment to one or the other kind of cell was random. The prisoners in the inside cells had a 24% higher frequency of sick-call visits, compared to those in exterior cells. The study author could not identify any design feature to explain this difference, and concluded that the outside view "may provide some stress reduction." Like prisoners, employees with views of nature at work report fewer headaches (as well as less job pressure and greater job satisfaction) than those without such a view[15] .

Other evidence of the healing effect of greenspaces is available from therapeutic settings. In a study of dental patients[16] , researchers placed a large mural of an open natural scene on the wall of a dental waiting room during some days, and removed it on others. On the days when the mural was visible, dental patients had lower blood pressure and less self-reported anxiety than on the days when it was taken down. In a study of psychiatric in-patients[17] , patients were exposed to two kinds of wall art: nature scenes such as landscapes, or abstract or symbolic art. Interviews suggested more positive responses to the nature scenes. Moreover, in 15 years of records on patient attacks on the wall art, every attack was on abstract art, none on a nature scene. These studies seem to show that viewing landscapes or nature scenes whether through a window or in pictures, seems to have a curative effect[18] .

Restoration from Stress, Frustration, Aggression, Violence

Restorative environments are hypothesized to help renew psychological resources that get depleted in environments that require effort to maintain attention, focus, or concentration[19] such as busy urban areas[20] . Greenspaces in cities are only beginning to be widely empirically studied for their restorative effects on human stress and frustration. Systematic methods of determining cause and effect have just recently been developed. In general, adults have reported that when they are stressed or depressed, going to natural settings in the outdoors can help them feel better[21] .

One theory of the effect of vegetation on humans is ‘attention restoration’ theory, where calming or fascinating environments reduce the need to direct attention as directing attention requires effort and leads to fatigue. Attention Restoration Theory[22] holds that Directed Attention Fatigue, the fatigue that comes from having to process the countless messages of busy environments, may be lessened in natural settings, leading to feelings of restoration. Views of vegetation and water such as rivers or lakes, through windows have been shown to restore attention and induce a calming effect[23] . Attention restoration may alleviate mental fatigue, reducing aggression and frustration - studies in inner-city Chicago show that mental fatigue is alleviated by the presence of nearby nature[24] , a recent study[25] , and another study of students[26] found that college students with natural views from their dormitory rooms had better attentional capacities than those with built views from their dormitory rooms. Other studies[27,28] show urban forests are used as privacy refuges, shelters or escapes from the everyday world.

Another theory of stress relief cause and effect is the 'defensible space' theory. Residential spaces that are well-used create social ties and social contacts, discouraging misbehavior by fostering informal surveillance[29] . Trees and vegetation play a role in creating spaces that encourage social contact[30] . The theory states that people like to interact in greenspaces and are more apt to create social ties and watch out for each other. A team of researchers is performing a series of large-scale studies regarding vegetation and built spaces in the inner-city of Chicago, and is finding a correlation that vegetation surrounding apartment buildings in the inner-city reduces crimes of property and violence[31] , reduces aggression[32] and domestic violence[33] in inner-city residents as well. Bringing people out into common spaces in the study area fosters a sense of community and creates informal support groups, perhaps strengthening the social fabric and relieving day-to-day pressures and frustration and thus lessening crime.

Perceptions of safety

The links between safety and trees are indirect. Although Kuo and Sullivan's work on theories of defensible space and inner-city residents shows a connection between vegetated spaces and lessened violence through increased casual social interaction, the vegetation *per se* appears to have an indirect effect, and casual social interaction is not consistently related to outcomes[34]. The results of Kuo and Sullivan's earlier paper, mentioned previously[35] , contradict this statement as a correlation was shown when examining police records that more vegetated areas reported fewer crimes of property and violence. Nonetheless, the U.S. Department of Housing and Urban Development (HUD) has implemented a Defensible Space program – including tree and shrub placement - into its policies[36] to ensure vegetation does not block sight lines or create places to hide.

First arising out of the defensible space theory were guidelines to ensure that vegetation best lends a perception of safety indirectly when it does not obstruct visibility and allows natural surveillance. Purposeful environmental designs that allow ease of surveillance and utilize access control to increase human safety fall under a broad umbrella called 'Crime Prevention Through Environmental Design' (CPTED). The design elements of CPTED allow for easy natural surveillance and control of territory through reinforcement and natural access. Although design guidelines have been in place for some time, little formal research has been performed to test the effectiveness of CPTED designs in reducing crime. One study analyzing published studies of small commercial businesses and their environmental designs[37] found that the design elements of CPTED were an effective approach to reducing robbery for those business types studied.

Accomplishment

Planting a tree or vegetable garden can provide a sense of accomplishment, effectiveness, or satisfaction in a person's day-to-day life with regard to helping the environment, their neighborhood or themselves[38,39] . This sense of accomplishment and effectiveness is a component of a small daily victory – a small sense of empowerment that can serve as a building block for other victories. A garden can also provide food security, a tangible benefit[40] .

Social belonging/community

A quarter-century of research has indicated that, in general, urban outdoor areas with trees are substantially more preferred than similar settings without trees[41] . Studies of inner-city housing developments consistently show greater use of outdoor areas that contain natural landscaping[42,43] .

Views of green space from home are also linked to a greater sense of well-being and neighborhood satisfaction[44,45] and urban residents tend to prefer interacting in spaces with high levels of green cover[46] . Some researchers[47] have found, in studies measuring the effectiveness of neighborhood planting programs, those residents who participated in planting their own trees[48] or in neighborhood tree-planting projects[49] are significantly happier with their neighborhood than residents of neighborhoods with little or no such participation, and tree survivorship increases with neighborhood participation as well.

Children

Urban children may be largely separated from natural settings in their everyday environment. The built environment that includes vegetation may be their only contact with nature without traveling outside of city limits. Few studies exist measuring children’s use of the outdoors or greenspaces for comfort, relief or restoration in response to the complexities of the urban environment. Children’s ideas of the utility of greenspaces differ than that of adults - children often ask ‘what can I do here?’ - preferring to actively use a place rather than considering the aesthetics of a place first, as adults do[50] .

One study[51] evaluating the effectiveness of a healing garden at a children’s hospital in San Diego, CA, USA found that the garden was perceived as having a healing benefit, and suggestions for improvement included adding more trees and things for children to ‘do’. A study of children in a rural setting found levels of nearby nature moderate the impact of stressful life events on the psychological well-being of the children studied. Specifically, the impact of life stress was lower among children with high levels of nearby nature than among those with little nearby nature[52] .

Another study[53] found that girls in inner-city housing measured better on self-discipline tests when vegetation was present around their home. No such improvement was found in boys. A study measuring task performance and mood[54] in a controlled setting found that undergraduate men performed better at certain tasks when they viewed leafy plants than others who could not see the plants during certain task performance. The researchers concluded the presence of plants might positively affect creative work. These results follow the Kaplan's Attention Restoration Theory of Directed Attention Fatigue, although both papers were preliminary works. One study found living in a green environment can improve school performance[55] , although the study cautioned against generalizing its findings.

A few studies have found green places can be very important to children. Children's play in places with vegetation can support children's development of skills and cognitive abilities[56] and lessen the symptoms of Attention Deficit and Hyperactivity Disorder (ADHD)[57] . A comparative study conducted in Sweden[58] found that children in a day care center with a natural play area had better motor coordination and better attentional abilities than children in a day care center without a natural play area.

Summary

Intuitively we know we tend to feel better when surrounded by greenery. Only recently have theories been developed and tested to determine exactly why this is so. Many research agendas are exploring the strengthening understanding between green spaces and human preference and well-being. These preferences are actively being researched and generalizing these findings is difficult. Most research into urban greenspaces with respect to well-being is directed in the area of restoration of attention with "attention" being defined as 'focus' or 'concentration'. The complexity of the human psyche and the urban environment makes cause and effect difficult to determine at this time. However, much interesting research is now being conducted and the findings here may be soon superceded by new knowledge.

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Economic Benefits of Urban Forests

Urban forests and individual urban trees have measurable economic benefits, which can be translated into financial terms and recognized as assets having investment value to communities or individuals. For example, single mature shade trees provide annual benefits (both consumptive and non-consumptive) that range between US $40-80 per tree, while management costs are US $15-30 per tree, providing a net benefit[1] 25-50 per tree or a return on investment of 266%.[MCM1]

The economic benefits of urban forests are mostly conferred by the tree canopy covering a surface (especially an impervious surface), intercepting or absorbing air pollution, or intercepting solar radiation. These benefits are generally either closely tied to human-created infrastructure or values that arise out of increased quality of public goods. These economic benefits are in addition to the aesthetic, mental and physical health, conservation, and natural benefits humans derive from the urban forest.

Examples of economic benefits that are provided by urban forests include:

- Energy conservation by shading and reducing wind speed on buildings
- Positively affecting air quality (generally)
- Removal of atmospheric carbon dioxide and sequestration of carbon
- Reduction in stormwater runoff
- Increasing property values
- Increase in businesses’ attractiveness to customers and an increase in a willingness to pay by consumers
- Noise attenuation
- Urban wood waste

Economic benefits of urban forests have been calculated along gradients from single-tree benefits to city-wide benefits to national benefits. Single-tree economic benefits for popular shade trees have been calculated. For small cities, urban forest economic benefits have been shown to outweigh costs by almost 2:1[2,3] ; similarly, urban forest benefits outweigh costs by a similar ratio in larger cities[4,5] , and total urban forest value estimates in the United States exceed US $2 trillion in one study[6] .

Costs must be considered alongside benefits. A separate section below details the overall cost-benefit of urban forests. The preponderance of evidence shows that the benefits far outweigh the costs of the urban forest.

Energy Conservation

The urban forest conserves energy by producing shade, blocking wind, and cooling air temperatures. Trees and shrubs conserve building energy use by shading buildings in summer and blocking wind in winter. When building energy use is conserved, pollution emitted from power plants is reduced. Typically, estimated electricity demand in cities increases by 2–4% for each 1°C (1.8 °F) increase in temperature[7].

Shading

Shade is an important benefit derived from the urban forest canopy. Heating and cooling savings from trees are highly dependent on local climate, building and HVAC characteristics, energy prices, as well as tree location, size, and species. Net savings from tree shade tend to be greatest in the hottest sunbelt regions, where shade is least detrimental during the winter heating season. Annual net savings from a large public tree can be US $10. Cooling benefits are greater from trees on north-south running streets that shade east- and west-facing walls, than from trees on east-west streets[8] .

In general, individual homes with well-sited trees in hotter climates have been found to have their net energy costs reduced by an estimated 8-12% per year[9] . Simulations show a nationwide reduction in peak cooling demand of an estimated 2-10% per year[10] is realized via the urban forest. Trees sited on the west, southwest, and east, respectively, of buildings realized the greatest savings[11] and three trees surrounding a house in these positions realized a 10-50% savings in annual energy, with well-insulated buildings realizing the greatest savings. The existing tree canopy saved homeowners from US $16 to US $69 in summer cooling costs in residential areas, with an average of about US $38 per home. The greatest savings were found in the study site with the highest tree canopy percentage, although high tree canopy percentages did not always correlate to significant energy savings[12] . Studies using one well-placed shade tree per house found that one tree can avoid peak cooling demands (nationwide) by an estimated 2-8% per year[13] . Other studies in temperate climates have found per-tree energy savings as 1.3% for annual heating energy savings, 7% for annual cooling energy savings, and 6% for peak cooling demand reduction[14] .

A paper found that increasing the total canopy cover of the urban forest by approximately 10%, approximately three trees per building, can save an estimated 5-10% or US $50-90 per house per year in total energy use[15] . Homes having a large number of shade trees nearby may realize substantial savings. A study of two houses in California that were shaded by 16 deciduous trees, eight tall and eight short, found cooling savings of 30%[16] .

Tree canopies can avoid costs as well. A study[17] that found 12% savings per year (US $18.5 million) in Sacramento air conditioning savings and avoided costs of US $6 million per year, mainly in deferred investment in new generation capacity. Tree shade avoids CO_2 emissions through decreased power generation[18] . Estimates that a single tree planted in Los Angeles avoids the combustion of 18 kg of carbon annually, even though it sequesters only 4.5–11 kg, and a 4-city study estimated a 92 kiloton reduction per year in carbon emissions simply by siting 4 shade trees around houses in those cities[19] .

Tree shade can increase the cost of heating residential structures. The shading reduces insolation used for heating in winter months, even with deciduous trees[20] .

The shade cast by trees can also increase the longevity of built surfaces – especially pavement. Few studies have been conducted to date, but one paper[21] claims that in a hot, arid climate, increasing street tree shade by 20% increases the pavement longevity condition index (a measure of the amount and severity of surface distress) by 11%. The paper states once large-stature shade trees have matured, their shade can extend the resurfacing cycle from 6 to 13 years, reducing preventive maintenance costs by as much as 50%.

Lower temperatures

Urban trees reduce ambient air temperature by interception of solar radiation and by evapotranspiration. The latent heat of evaporation cools the surrounding air[22] .

Analysis of temperature trends for the last 100 years in several large U.S. cities indicate that since about 1940 temperatures in urban areas have increased by about 0.5–3.0°C[23]. Typically, electricity demand in cities increases by 2–4% for each 1°C increase in temperature. A study estimated that 5–10% of the current urban electricity demand is spent to cool buildings just to compensate for the increased 0.5–3.0°C in urban areas[24] . A study[25] in Athens, Greece found when the mean heat island intensity exceeds 10°C, the cooling load of urban buildings may be doubled, the peak electricity load for cooling purposes may be tripled especially for higher set point temperatures, while the minimum performance value of air conditioners may be decreased up to 25% because of the higher ambient temperatures.

Reduced wind speed

Vegetation deflects wind by obstructing, guiding, deflecting or filtering[26] . Obstructing, deflecting or filtering wind in the winter retains energy, but reduces cooling effects in warm seasons. Guiding wind in warm seasons can produce a cooling effect.

Researchers[27] have found the impact of simulating wind reduction on heating- and cooling-energy use of typical houses in cold climates indicated a 30% uniform increase in urban tree cover can reduce winter heating bills in urban areas by about 10%, and in rural areas by about 20% per year.

A study[28] combined the effects of increasing shade and reducing wind speed on air-conditioned residences and realized annual savings of 2-23%, depending upon tree density and city.

Trees can also change larger-scale wind flow patterns, usually resulting in reduced wind speeds; this may reduce mixing out of pollutants such as ozone in the urban microclimate, but reduced wind speeds can also help save energy in cold climates by reducing heat dissipation[29] .

Air quality

The pattern of spatial arrangement of urban forests makes it difficult to precisely determine their contribution to large-scale air quality. Uncertainties in the current understanding of urban climatologic and atmospheric processes further complicate quantification of effects. However, advances are being made in this field.

The urban forest canopy positively affects air quality directly by receiving and filtering dry deposition (without precipitation) of airborne particulate matter and by absorbing gaseous pollutants through their leaf stomata. Absorption rates are affected by local differences in climate, pollutant concentrations, and canopy cover and structure. Interception of pollutants is not permanent, as a dry particle may be resuspended into the atmosphere, washed off by precipitation, or dropped to the ground when leaves, needles or twigs fall[30] . The urban forest canopy affects air quality indirectly mainly by avoiding hydrocarbon release – decreased energy demands result in lower emissions, and by decreasing reaction rates of chemical processes relating to smog (detailed in 'Heat Island Mitigation' in the Environmental Services section of this paper).

A number of studies have attempted to quantify the amount of dry deposition received by canopies. A study in Sacramento, CA estimated that approximately 1,457 metric tons of air pollutants are absorbed annually by Sacramento County's 6 million trees, at an implied value of US$28.7 million[31] . The average uptake per day was 5.9 tons. Pollutant uptake rates decreased with decreasing tree canopy cover along an urban-to-rural gradient. This study did not include effects from air temperature decrease or BVOC emissions. In 1994, trees in New York City removed an estimated 1,821 metric tons of air pollution at an estimated value to society of US$9.5 million[32]. Air pollution removal by urban forests in Atlanta was 1,196 tons with an estimated value if US$6.5 million, and Baltimore's urban forests removed 499 tons at an estimated value of US$2.7 million. Pollution removal per m^2 of canopy cover was fairly similar among these cities (New York: 13.7g/m^2/yr; Baltimore: 12.2 g/m^2/yr; Atlanta: 10.6 g/m^2/yr.)[33] . The preceding values are based on models and model assumptions.

Another study quantified the air quality benefits derived from the urban forest of Brooklyn, NY and found Brooklyn's trees currently store approximately 172,000 metric tons of carbon with an estimated value of US $3.5 million. In addition, these trees remove about 2,500 tons of carbon per year (worth an estimated US $51,000/yr) and about 254 metric tons of air pollution per year at an estimated value of US $1.3 million/yr.[34] In 1991, an estimated 6,145 tons of air pollutants, at an estimated value of US $9.2 million was removed by Chicago's urban forest[35] .

A series of new studies is analyzing the forest cover in a number of American cities[36] . Among the data points collected is the amount of air pollution absorption by the various urban forests of these cities, along with the dollar value of this absorption. A summary of the air pollution absorption findings is in Table 1.

City trees can have a negative impact on air quality by reducing the dispersion of pollutants within the urban canopy layer by lowering wind speeds, emitting biogenic volatile organic compounds (BVOCs) that are involved in ozone formation, and indirectly increasing emissions of pollutants associated with tree care activities (e.g., chain saws, chippers, trucks, and decomposition). A study found increased ozone concentrations resulting from increased planting of tree species in Los Angeles that are medium- and high-emitters of BVOCs[37] . A study of a hypothetical shade tree planting in Sacramento that included costs associated with BVOC emissions found that benefit-cost ratios ranged from 2.2:1 to -0.8:1 depending on assumptions regarding rates of pollutant deposition and BVOC emissions[38] .

Table 1. Air Pollution Absorption by Selected Urban Forests.

City/Region	Avg. Canopy Cover (%)	Air Pollution Absorption (M lb.)	Absorption Value (US $M)
Buffalo	12	0.4	1
Charlotte	53	17.6	43.8
Chesapeake[1]	36	711	1508
Denver	6	2.2	5.3
New Orleans	24	2.9	7.1
Portland	24	178	419
Roanoke	47	5.9	14.6
San Antonio	27	926	22.1
San Diego	7	4.3	10.8
Washington DC	46	20	49.8
United States[2]	**27.1**		

1 Charlottesville, VA
and Harrisburg, PA
2 Datum from United States Forest Service "National Urban Forest Assessments in the United States" on-line reference at http://www.fs.fed.us/ne/syracuse/NatUFAssessments.htm

A study estimated that a single tree planted in Los Angeles avoids the combustion of 18 kg of carbon annually, even though it sequesters only 4.5–11 kg, and a 4-city study estimated a 92 kiloton reduction per year in carbon emissions simply by siting 4 shade trees around houses in those cities[39] .

Water Quality

The human built environment favors hardscape or paved areas such as concrete, asphalt - even lawns - and buildings that reduces the ability of soil to absorb precipitation when compared to rural or non-paved areas. The resulting greater surface flow increases peak discharges of stormwater, picks up pollutants such as automobile oils, liquids and metals, lawn fertilizers, cleaners, etc., and slows the rate of aquifer recharge[40] .

In many communities, the rate and volume of stormwater runoff have increased beyond the capacity of existing stormwater drainage systems, especially older cities with combined sewer systems. The United States Environmental Protection Agency has published a literature review[41] detailing the scope of the problem and describing Best Management Practices (BMPs) in various cities throughout the world. BMPs include retention ponds, naturalistic landscaping, wetland buffers, and others depending upon location and topography. Many urban forestry activities, such as creating open spaces, saving trees on construction sites, and planting trees after construction, can help reduce the amount of storm-water runoff that enters the drainage system.

Studies note that a reduction in overall canopy cover increases stormwater discharge and decreases infiltration of precipitation. In Forest Park, GA, USA, the average tree canopy density declined from 22% in 1974 to 17% in 1996, resulting in a 28% increase in runoff, which would require a stormwater system equivalent in value to a US $4.5 million system. The stormwater retention capacity was reduced from US $15.8 million in 1974 to US $11.3 million in 1996[42] . The Philadelphia region analyzed the loss of canopy cover and found that a 1% loss of canopy cover resulted in the Delaware Valley's urban forest no longer being able to detain almost 53 million cubic feet of stormwater, a service valued at US $105 million in stormwater containment construction[43] .

Noise attenuation

Noise from traffic and other sources decreases the quality of life in urban areas. The overall costs of noise have been estimated to be in the range of 0.2 –2% of GDP in the EU[44] . In the United States, it is estimated that the damage cost of noise is likely in the range of US $3-5 billion per year[45] . The depreciation of home values by noise has been estimated as well. A study[46] analyzed various European and North American studies and found each additional decibel of noise decreased property values by a mean of .55%.

Vegetation can attenuate noise, but applications of vegetation to date to effectively attenuate noise have been problematic at best. One robust study[47] , however, has quantified type and height of vegetation to best attenuate noise. The study found density, height, length and width of tree belts are the most effective factors in reducing noise rather than leaf size and branching characteristics. Noise diffusion is obtained via density, height, length and width, and noise absorption is obtained via leaf size and branching characteristics. Diffusion was best at reducing noise, and the higher the density of vegetation, and the more foliage and branches to reduce sound energy, the greater the scattering effect. Width of vegetation belts is the other significant noise reduction factor.

Property values

Studies from various areas in the United States have found that large, healthy trees positively impact residential property values by increasing the aesthetic appeal of the property or curb appeal. The values of houses in neighborhoods with extensive tree canopies generally are found to be higher than those of comparable houses in neighborhoods without trees[48,49,50,51] .

Research comparing sales prices of residential properties with different tree resources suggests that people are willing to pay 3-7% more for properties with ample tree resources versus few or no trees[52] . A comprehensive study of trees and property value in the American Southeast, based on reported sales prices, found that each large front-yard tree was associated with about a 1% increase in sales price[53] . This increase in property value resulted in an estimated increase of US $100,000 (1978 dollars) in the city's property tax revenues. Studies in California and the Pacific Northwest of small- and medium-sized cities found similar percentages[54] . An empirical study based on data from the sales of terraced houses in the district of Salo in Finland found according to estimation results, a one kilometer increase in the distance to the nearest forested area led to an average 5.9 percent decrease in the market price of the dwelling. Dwellings with a view onto forests are on average 4.9 percent more expensive than dwellings with otherwise similar characteristics[55] .

Model studies of rural properties in the rural-wildland interface of California found trees contributed between an estimated 5% and 20% to the property value, depending upon forest density and health characteristics[56] . A hedonic model applied in Finland found a positive influence on apartment prices when situated near watercourses, wooded recreation areas, or districts having an increasing proportion of forested area[57] .

Proximity to open spaces positively affects property values. Real estate markets show many people are willing to pay a higher price for a property located close to a park than for a property that does not offer this amenity. Many cities utilize this fact to plan for long-term tax revenues and the term is called the "proximate principle". A study of the literature[58] found strong support for the proximate principle and suggested property adjacent to urban parks may have values 20% higher, with values being 10% higher up to 3 blocks away. The study found wide agreement that a park's proximate value had substantial impact up to 500 feet and that in the case of community sized parks it extended out to 2,000 feet, and the rural studies scrutinized showed empirical evidence to support not only the proximate principle, but also to refute the conventional wisdom that creating large state or federal park or forest areas results in a net reduction in the value of an area's tax base. A study using detailed GIS data and modeling in Portland, OR, USA[59] found correlation that residences within 1500 feet of a park had positive effects on property values, with increasing size having larger positive effects. A non-peer reviewed study[60] using hedonic pricing in rural areas found that within 400 meters of a house, open space had the largest positive effect on property values, whereas large-lot, single-family residential land had a positive effect almost as large. Commercial, small-lot single-family residential, multi-unit residential and industrial land uses were less favorable for nearby property values. These values reversed at distances 400-1600 meters from the property. A study found proximity to wetlands positively affected property values[61] , while another study in the Netherlands of completed real estate transactions[62] found increased property values for houses built after 1970 and overlooking water (8-10%) or open space (6-12%) or having attractive landscaping (5-12%), as opposed to houses lacking those features. A study found that residential areas with open space contributed more in revenues than they required in services and were found to be net assets when considered in light of taxes generated compared to cost of services they require[63] .

Management of open space may affect property values as well. A study using a hedonic model found certain forestry practices could reduce property values. Clearcuts and even-aged stands negatively impact property values, while maintaining mature or tall stands of trees retains property values[64] .

Healthy street trees positively affect property values. A study of Modesto, CA found the typical large street tree increased property values by US $1.93/m^2 of leaf surface area[65] (a typical medium-sized tree may have 25 m^2 – 64 ft^2 - of leaf surface area)..

Businesses

Recent studies have constructed methodologies to understand how green streetscapes affect consumer behavior. Past studies merely added up total sales data, such as quantification of consumer economic impacts as a result of urban forests in California, finding that urban forests accounted for at least US $3.384 billion in total sales during a 12-month period in the early 1990s[66] .

Generally, consumer behavior is characterized by ‘willingness-to-pay’. Recent work[67] found respondents to a survey were willing to pay an additional 12% for goods associated with a vegetated streetscape. Customers were willing to pay extra for the experience of shopping in an area with aesthetic beauty augmented by an urban forest. A large study[68] corroborated an additional willingness-to-pay, and found that customers were willing to travel farther to reach well-vegetated businesses, and while trees or landscaping were not the most important consideration for shoppers, trees and exterior landscaping were among the most preferred amenities. The quality of landscaping along approach routes to business districts has also been found to positively influence consumer perceptions[69] .

There is corroborating work on the validity of emotions being connected to purchasing behavior[70], and that consumers' hypothetical willingness-to-pay responses are effective predictors of actual market behavior and some findings show that consumers who state that they are willing to pay a premium, within bounds, have a higher likelihood of actually buying the product in question, implying that consumers' actions in the economic experiments typically validate their survey responses[71] .

A study using a detailed hedonic pricing model on existing commercial building rents[72] found a clear relationship between quality landscaping and higher office rental rates. Quality landscaping positively impacted rental rates by 7%, as did good building shade. Conversely, vegetative barriers reduced rental rates by approximately 7.5%. The New York/New Jersey study[73] did not prove tangible economic benefits for developers of commercial sites. Rather, it implied some cost savings occurred from preserving forested lands on the site and planting trees throughout the landscape, which reduced the required size of the onsite stormwater management systems.

Businesses also experience increased productivity when their employees are exposed to greenspaces. Desk workers who can see nature from their desks experience 23% less time off sick than those who cannot see any nature. Desk workers who can see nature also report greater job satisfaction[74] .

Cost-Benefit Analyses

When all benefits are considered together as a whole, healthy urban forests return more benefits than their costs. Cost-benefit ratios of trees have been calculated for individual tree species, for small-, medium-, and large-sized cities, and estimated for the national urban forest.

Cost-benefits of single tree species have been calculated for 10 species for the city of Modesto, CA, USA[75] . For that city, London plane was an outstanding performer, with a benefit:cost ratio of 24:1, with gingko, camphor, zelkova and Chinese hackberry all returning benefits at a greater than a 5:1 ratio.

Cost-benefits of urban forests have been calculated in a handful of studies[76,77,78,79,80] . Davis, CA, USA – a small city - realized a 3.78:1 benefit:cost for the publicly-maintained urban forest, or approximately US $21.30 per resident[81] . Cost-benefits of medium-sized cities have been calculated. One study[82] compared the urban forest structure of two cities; Modesto, CA, USA’s public urban forest has a benefit:cost of 1.85:1, and Santa Monica, CA, USA has a benefit:cost of 1.52:1 for its public trees. Modesto saves substantially more energy with a hotter climate and Santa Monica has a higher aesthetic value because of higher real estate prices. A study of the benefits of Chicago’s urban forest[83] found that benefit:cost was 2.83:1. Energy savings and aesthetics were major benefits, although benefits were highly site-specific.

Urban Wood Waste

There is a growing market for products made out of wood (especially hardwood) from trees in the urban forest. The technology for small, portable sawmills exists that allows milling of just one or two trees. In the last 10 years in California, 600 portable owner-operated sawmills have emerged[84]. Although there is no measurement of the total value of urban wood products in the United States, there are numerous small niche markets capitalizing on unique urban hardwoods[85] and other wood products such as chips, mulch and compost.

Summary

Urban forests have many clear, measurable economic benefits to provide a positive return on investment. Proper siting, design and selection of trees can allow tree canopies to help cool cities, help reduce and absorb air pollution, decrease energy usage, and help attenuate noise. Proper species selection and shading can increase pavement longevity, and shaded parking spaces can reduce vehicle emissions from parked cars in warm temperatures. Proper siting and selection can reduce stormwater runoff and increase infiltration, reducing mitigation costs and restoring water quality. The aesthetic qualities of trees can increase residential property values, increase commercial rents, and quality of landscaping may influence business customers' willingness to pay.

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Other Values of the Urban Forest

Urban forests have some less commonly considered benefits. The tourism industry, in some areas, depends upon certain tree festivals, beautiful gardens or outstanding natural areas. Some towns or hamlets may be partially defined by a tree or trees in the area. Societies may place trees at the center of some cultural values, as with western societies and Christmas trees. As municipalities struggle with conflicting priorities, it is certain that people will be needed to manage the urban forest; the last topic in this section briefly discusses jobs in arboriculture and where these jobs are posted.

Tourism

Urban trees can promote tourism. The world's oldest banyan tree, 570 years old and covering 5.2 acres, is the centerpiece of a tourism marketing campaign for a town in southern India[1] . Poinciana trees are frequently mentioned for Caribbean tourist attractions. Many tourist attractions in the UK include trees or woods[2] . Eco-tourism is increasingly relying on trees as a part of traditional cultures to attract visitors[3,4,5,6] . Cherry blossom festivals throughout the world attract thousands of visitors. Washington, DC hosts the annual National Cherry Blossom Festival, attracting more than 700,000 people each year[7] . Macon, GA, USA hosts a cherry blossom festival that is one of the top 100 events in North America[8] . Japan holds hundreds of cherry blossom festivals each year, occurring from January to June[9] . Scotland holds a large tree festival annually[10] .

Heritage Trees

Many cities have organizations that identify, honor and protect important trees in the community[11,12,13,14,15,16,17] . Heritage trees can help define a town, area, or even an ancient country, such as Lebanon and its cedars.

Cultural Values

Trees may help shape the legends and culture of an area[18,19,20] . Greenspaces and gardens can define cities, whether historical cities such as Babylon, Hellenic Greece, Rome, Mayan, Inca and Aztec civilizations, and many Chinese cities, to the styles we recognize today from Renaissance gardens[21] . Some historical gardens persist today and are highly valued symbols of a society, such as Japanese gardens[22] , steeped in ritual and history. The British cottage garden, the Japanese zen garden, a walled Indian garden, all carry cultural significance and help define spaces within cities.

Job Opportunities

The urban forestry field is expanding. There are currently more than 15,000 International Society of Arboriculture (ISA) certified arborists, and additional ISA classifications entitled Certified Arborist, Utility Specialist, and Tree Worker/Climber Specialist; still in the developmental stages are the Municipal Specialist and Board Certified Master Arborist Certification[23] . The United Kingdom has a similar organization called the Institute for Chartered Foresters that publishes a list of their certified consultants[24] . The International Union of Forest Research Organizations (IUFRO) is a worldwide Non-Governmental Organization that has an urban forestry division[25] . The British National Community Forest Partnership has a number of partnerships with agencies, governments, and other authorities[26] .

The tree foundation of Kern (CA, USA) has a general publication entitled '50 careers in trees'[27] . Urban foresters are needed in city, county, and state governments, non-profits, and in the private sector - with titles such as 'Utility Forester', 'Forestry Analyst', 'Forester', etc. Jobs in the urban forestry/arboriculture field are posted:

- *Tree Care Industry* - publication of the National Arborist Association: http://www.natlarb.com
- *Journal of Forestry*, published by the Society of American Foresters (SAF): http://www.safnet.org
- TreeLink posts a job index at: http://www.treelink.org/forum/viewforum.php?f=3
- Ferrells Jobs in Horticulture: http://www.giantads.com/
- Tree Care Jobs: http://www.treecarejobs.com/

In addition, the following professional organizations are either directly or indirectly associated with arboriculture, urban forestry, greenscapes, green infrastructure, or trees:

- American Horticulture Society: http://www.ahs.org/
- American Planning Association: http://www.planning.org
- American Society of Landscape Architects: http://www.asla.org
- International Society of Arboriculture: http://www.isa-arbor.com/
- National Arborists Association: http://www.natlarb.com
- Professional Grounds Management Society: http://www.pgms.org/

Summary

Greenspaces in cities can carry great cultural significance and can be vital resources for inhabitants. Residents continue to honor these traditions by memorializing spaces or ensuring heritage trees are recognized. Municipalities must ensure the urban forest resource is sustained and therefore jobs exist for tree planting, establishment, maintenance, and disposal.

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Addressing Community Concerns with Trees

Although lawn, park and street trees confer many benefits, most unseen, conflicts caused by urban trees are often seen and remembered when considering the values of urban trees. Trees require maintenance, may conflict with infrastructure such as sidewalks, sewers, and overhead power lines, and can fail in storms.

Generally, conflicts occur either below-ground or above-ground. Both types of conflict are perhaps best considered as human infrastructure not being conducive to tree growth, a consideration expanded upon below.

With the exception of a tree being diseased or old and near death, the most common reason for tree-infrastructure conflicts is not adhering to the adage ***right tree, right place***.

Below-ground background

The most common infrastructure conflicts come from tree roots. Trees need adequate soil volume for their roots to absorb nutrients and water to maintain metabolic functions[1] . Urban soils are frequently of poor quality and often inadequate to allow woody plants to flourish[2] . Trees planted next to the street in tree lawns (‘tree strips’, ‘planting strips’) must be adapted and of sufficient size to be ‘well-behaved’ in a space- and resource-limited environment. Tree diameter (DBH) is directly related to infrastructure damage[3] . There is a linear relationship between tree DBH, distance from concrete and probability of damage. A 30cm DBH tree 1m from concrete has an approximately 35% probability of damage, but 2m from concrete the probability is near zero. Put another way, one must have a 50cm DBH tree 2m from concrete to have a 35% probability of damage[4] .

Concrete sidewalks may actually foster root growth. The underside of sidewalks are cooler and moister than the surrounding soil, offering opportunities for root hairs to elongate in search of water and nutrients[5] ; roots take advantage of the pore space created due to thermal differences between material interfaces, - materials such as pipes, curbs, and pavement. Any material out of thermal equilibrium with neighboring materials creates water vapor pressure changes and water condensation at the interface - providing exactly what roots are looking for. Thermal changes in materials may crack gaskets, seals, connectors or the infrastructure material, creating openings for roots. Construction or repair may damage infrastructure, allowing tree roots to penetrate. Roots react to cracks in pipes or sidewalks and optimize resources in the often resource-poor urban environment.

Above-ground background

Above-ground conflicts are often created by woody plant canopies' sheer size. Inadequate design consideration to a plant's ultimate size may lead to conflicts with overhead utility lines, signage and lighting. Often a belief that a plant's ultimate size can be 'managed' - such as keeping the canopy off the house or keeping a large shrub below window height by pruning, causes conflicts. Also, managing a plant to keep it in bounds weakens the structure and physiology of the plant, leading to more conflicts[6] . Many cities have guidelines or even ordinances to ensure correct species are selected for trees near or in the public right of way, in order to avoid conflicts. Part of management is being aware of the potential risks and conflicts associated with trees, identifying them, and then minimizing these risks and conflicts within the constraints of management objectives[7] .

Below-ground conflict consequences

Tree roots in urban areas often conflict with the built environment. Hardscape conflicts caused by public trees include sidewalk and street heaves, curb breakage and gutter cracking, while hardscape conflicts by private trees include driveway heaves, and swimming pool and foundation interference. Roots can also infiltrate sewer and water mains and impede access to buried utilities. Heaved public pavement can be problematic for municipalities, resulting in large expenditures for trip-and-fall claims, root pruning and pavement replacement. Conflicts with water and sewer pipes are more variable, although in some areas almost 50% of sewer blockage is caused by roots.

There is a relative abundance of empirical studies enumerating the extent of root-infrastructure conflicts. One study[8] of infrastructure conflicts in 18 cities in California, USA found that annually, approximately US $71M (year 2000 $) is spent statewide on conflicts between street tree roots and sidewalks, streets, curbs and gutters. Approximately US $23M is spent on sidewalk repair, US $12M on curb and gutter repair, and US $10M on trip-and-fall claims and legal staff expenditures. In addition, approximately US $7M is spent annually removing and replacing trees in conflict with hardscape, and US $6M is spent on programs administering inspection and repair. These figures do not include damage by trees located in parks, yards, or other off-street areas[9]. Another study[10] reiterated previous findings of street tree conflicts with infrastructure costing US $4.28 per tree, or 25% of budget, and 20% of all trees removed were due to infrastructure damage - the main reason for removal and changing species. Another study[11] enumerated street tree repair costs in California, USA per capita at US $.88 and the frequency of sidewalk repair was 1 per 99 street trees, with the average repair cost at US $480.00. Although not all municipalities pay for infrastructure repair from public trees[12] , some municipalities push the costs down to the homeowner, creating an unfavorable image of trees.

Tree root-sewer conflicts are another major expenditure in urban areas. Less empirical study is available for sewer conflicts as opposed to sidewalk conflicts. Roots provide anchorage for trees, in addition to being organs of nutrient and water absorption. Especially for open-grown trees (as those in urban areas), deep and spreading root systems are essential to hold trees and large plants against strong winds, especially in wet soils[13]. A comprehensive study[14] suggested that the main reasons for root intrusion into sewer systems are that the infrastructure is poorly built. That is, engineering and/or design failures such as poor construction, excessive loading, inadequate connections and/or third party interference are responsible for root intrusion into sewers. A survey in Sweden[15] found that among 232 municipalities, 99% were affected by root intrusion causing serious disruption. Although the survey had issues with enumerating the extent of the damage, among the findings were older concrete pipes were most likely to be affected, and trees in the genera *Populus* and *Salix* (poplar and willow) were most likely to be affecting sewers. The findings are consistent with the standard literature[16] , which describes poplar, silver maple, and willow as especially problematic and avoidance of any fast-growing species near sewer lines or septic fields. In addition, joints or barriers tight enough to prevent microscopic root hairs from gaining access are best in preventing root problems in sewer lines.

Above-ground conflict consequences

Many above-ground conflicts are again a result of not following the adage *right tree, right place*. Lessening the likelihood of above-ground conflicts is the purpose of *species selection*. There is no perfect tree, however[17] , and species selection is a compromise among plant function, site adaptation, and amount of care the plant will require. Each site is different and the particulars of a species must be taken into account when assessing a site for tree placement. Conflicts with infrastructure are often a result of poorly thought out species selection and location.

Above-ground conflicts fall into the general categories of hazard (such as falling limb or power line interference), visual obstruction (such as of a view or a sign), nuisance (such as fruit or leaf drop or excessive shade on the landscape), or health (e.g. allergens).

Hazards are the most serious above-ground conflict. All trees are at risk of failure, some more than others. As trees increase in size, and age, the risk of failure increases[18] . There are other factors that also influence risk of failure. Past disturbance history such as trenching, construction compaction and root pruning, past cultural practices such as watering and plant placement, and past injury history. Eventual failure for most trees is inevitable, especially for trees in high-stress urban environments, where average life spans are considerably lower than in the wild[19] .

Generally, falling limbs or even entire trees falling over are the result of structural defects in the tree, and not the mere existence of the tree itself[20] , although an affliction called ‘summer branch drop’ can occur during or following hot summer or fall days[21] , and some trees without defects can fail in major storms[22] . Structural defects in trees can be obvious or hidden, and regular inspection programs which are problematic in times of tight municipal budgets or economic times, are perhaps the best insurance against injury or damage from falling limbs. Certain species ‘self-prune’ their limbs as well, especially *Platanus* and *Zelkova*[23] ,which may lead to instances where injury or damage is more likely. Utility pruning of limbs to prevent interference with infrastructure is a hotly-debated issue in areas of the country where utilities are cutting back on utility pruning[24] , though both wild and urban trees contribute to this issue. Again, species selection, especially under wires is a concern and many municipalities have ordinances restricting species under utility lines.

Obstructions can result from a limb obscuring a traffic sign or street light, or a tree canopy obstructing a viewshed. Species selection or design issues usually cause these instances though plant placement or lack of maintenance are also reasons why plants obscure signage or lighting.

Nuisance is commonly cited as the reason for complaints about trees, or conversely, ease of maintenance is a good reason to choose a particular species. One study found[25] private trees needing maintenance by professionals, such as pruning of a tall tree or spraying of a canopy, may or may not receive appropriate treatment.

Adverse health effects can occur from certain tree species which are moderately or highly allergenic[26], either from wind-borne pollen[27] or hairs on leaves or petioles. The majority of tree pollen, however, falls within the drip line of the tree[28], although on windy days pollen can be carried many hundreds of feet from the tree.

Summary

Knowing the ultimate size and growth characteristics of a woody plant will reduce the need to manage conflicts far in the future, when resource availability is unknown.

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Summary

The number of empirical studies regarding the benefits of the urban forest is growing rapidly. Approximately 375 studies, plus approximately 50 newspaper and periodical articles were examined for this literature review. There is great confidence that the large majority of important work and representative findings from important studies are presented here.

The following general conclusions about the benefits of urban forests can be made from this literature review, the details for which can be found in the individual sections preceding these conclusions:

1. The urban forest canopy likely has an overall positive effect on human physiological health, although direct causation and magnitude is difficult to precisely determine; the ability of the forest canopy to intercept and absorb gaseous pollutants and moderate microclimate, however, makes it clear that there is likely some positive effect from just these two factors alone.
2. The urban forest canopy positively affects air quality by absorbing and intercepting airborne gaseous pollutants, lowering ambient air temperatures, and moderating wind patterns. Lower ozone levels, less smog, lower heating and cooling energy demands, and less suspended particulate matter can be the results of this moderation of the urban microclimate. Urban forest canopies in large cities remove thousands of metric tons of pollution annually.
3. Dense urban forest canopies increase the amount of protection from ultraviolet rays from the sun.
4. The urban forest canopy slows precipitation runoff, allowing better infiltration and can lessen eutrophication and sedimentation of receiving waterways. It is abundantly clear that decreasing the overall forest canopy increases stormwater runoff and increases human mitigation costs.
5. Although just a few studies exist demonstrating so, greenspaces appear to facilitate human healing.
6. The mere presence of vegetation in the built environment appears to have a positive effect on promoting human physical health. Open spaces appear to foster physical activity – which is linked to lower levels of obesity and type II diabetes. Vegetation as a component of the built environment along walking routes may also help foster activity and promote non-motorized transportation, leading to less air pollution and better physical health.
7. Studies overwhelmingly show that humans prefer greenspaces and vegetation for social interaction or contemplative activities, exhibited in studies showing humans' preferential choice for residential areas with trees, feelings of restoration in greenspaces, relief from stress in nearby nature, and inner-city residents showing less aggression, violence and property crime in residential areas with greenspaces. Forthcoming studies on Attention Restoration Theory will shed further light on this topic.
8. Children prefer to play in natural areas, appear to have improved cognitive development in vegetated areas, and symptoms of ADHD appear to be lessened in greenspaces.

9. The urban forest canopy both stores carbon in its biomass and avoids carbon production by lowering energy demands for heating and cooling.
10. Properly configured (especially wide and predominantly evergreen) greenways can modify and attenuate noise by as much as 5-10 dBA.
11. Urban forests are connections between wild areas, and as such can possibly facilitate wildlife movement and provide habitat for many animal and plant species – in some cases, the only contact with nature some urban dwellers experience. Healthy urban forests can be an indicator of a healthier larger ecosystem.
12. The ecosystem services provided by the normal life functions of urban forests are the equivalent of billions of dollars worth of human-engineered systems.
13. Large, healthy trees and open space in residential areas raise property values and the wealthiest areas in cities are those that have the greatest amount of canopy cover.
14. Attractive greenspaces increase a businesses' attractiveness to customers and may result in a greater willingness-to-pay.
15. Attractive landscaping in commercial areas realizes greater profit potential for landlords.
16. One well-placed shade tree per house can avoid peak cooling demands (nationwide) by an estimated 2-10% per year, with more in hotter climates. This translates to US$16-69 (average nationwide about US$38). Increasing the number of trees substantially increases the savings.
17. Tree shade increases the longevity of built surfaces. The shadows cast from mature trees can extend the resurfacing cycle from 6 to 13 years, reducing preventive maintenance costs by as much as 50%.
18. In the cost-benefit analyses of urban forests performed thus far, urban forest benefits far outweigh costs, yet the overall urban forest canopy is decreasing.
19. Tree-infrastructure conflicts are generally: wrong tree - wrong place, the requirement to actively manage natural disease or death cycles, or deferred maintenance issues generally due to budgetary constraints.

Glossary

Albedo: The ratio of the amount of light reflected by a surface to the light falling onto it.

Biogenic: produced by living organisms or biological processes.

Eutrophication: A process by which an excess of plant nutrients, such as nitrogen and phosphorous from fertilizer, reduces the oxygen dissolved within a body of water, producing an environment that does not readily support aquatic life.

Evapotranspiration: The loss of water from a given area during a specified time by evaporation from the soil surface and by transpiration from plants

Hedonic: Of or relating to pleasure. Non-market resources are evaluated by hedonic models.

Infrastructure: the underlying foundation or basic framework of the system of public works of a country, state, or region, also the resources (as personnel, buildings, or equipment) required for an activity

Latent heat of evaporation: The amount of heat required to change a liquid into a vapor without raising the temperature of the vapor above that of the original liquid.

Mutualism: a close association between two different species whereby each species benefits from the relationship

Point source: A stationary location or fixed facility from which pollutants are discharged or emitted.

Riparian: pertaining to the banks of a river or other body of fresh water

Silviculture: The branch of forestry dealing with the development and care of forests.

Urban Forestry: A branch of forestry that has as its objective cultivating and managing trees and other woody plants and their associated vegetation in urban areas, and evaluating their contribution to the physiological, sociological, psychological (and sometimes economic) well-being of urban society.

Volatile Organic Compounds (VOCs): Organic chemicals all contain the element carbon(C); organic chemicals are the basic chemicals found in living things and in products derived from living things, such as coal, petroleum and refined petroleum products. VOCs constitute a wide variety of species that are very reactive in the atmosphere. They are broken down into simpler compounds that eventually lead to formation of ozone in polluted regions. Anthropogenic emissions of VOCs are closely tied to automobile emissions, with industrial processes also contributing significantly. Biogenic emissions of VOCs may be comparable to anthropogenic emissions in urban areas having large forested areas; about 90% of naturally emitted VOCs are from forests. (http://www.state.nj.us/dep/airmon/airtoxics/glossary.htm; http://sedac.ciesin.org/mva/shared.htmls/glossary.html)

Temperature Conversions

Fahrenheit to Celsius or Kelvin

1. Subtract 32 from degrees Fahrenheit
2. Multiply by 5
3. Divide by 9

Celsius or Kelvin to Fahrenheit

1. Multiply degrees Celsius by 9
2. Divide by 5
3. Add 32

C or K	F
1	1.8
2	3.6
3	5.4
4	7.2
5	9
6	10.8
7	12.6
8	14.4
9	16.2
10	18