ABSTRACT

KETO, EVAN MATTHEW. Composition and Estimated Value of Selected Benefits of Trees in Parking Lots in Raleigh, NC. (Under the direction of Dr. George Hess and Dr. Melissa McHale).

Trees are often planted in parking lots to reduce the environmental and visual impacts created by these paved surfaces. Using GIS, I estimated that parking lots cover approximately 10.9 square miles (5.97%) of the planning jurisdiction of Raleigh NC, USA. Parking coverage was found to vary greatly between different zoning classes, with the greatest coverage in commercial and industrial areas. I used a two-phase cluster sampling scheme to assess the composition of trees in discrete unpaved areas, called inclusions, within these parking lots. I classified inclusions into four types by size and shape: inclusions smaller than 1,000 ft^2 were categorized as compact "islands" or linear "slivers", and inclusions larger than 1,000 ft^2 were categorized as compact "chunks" or linear "rows". I measured more than 1,800 trees in 502 inclusions within 110 parking lots to determine the overall composition of trees and how this composition varied among different inclusion types.

Raleigh's parking lots contain 44,000 ± 24,000 trees (with 95% confidence), which were estimated to generate benefits worth more than one million dollars annually. Inclusions containing trees that appear to have been growing in fields or forests before lot construction ("preserved" inclusions) were found to have more trees, canopy, and basal area per acre than other ("designed") inclusions. Significant differences in tree composition and the proportion of trees meeting Raleigh's mature shade tree size goals were associated with the size and shape of the inclusion used. At the individual tree level, a disproportionately high number of

willow oaks and trees in larger inclusions were observed meeting Raleigh's size goals for mature shade trees.

This study provides a methodology for assessing the composition of trees in a city's parking lots, which allows comparisons to be made among different types of parking lots, inclusions, and trees. While few studies have addressed the composition of trees in parking lots, this area of research has value for lawmakers, urban foresters, and parking lot designers. With additional research, we may better understand how to maximize the ecosystem services provided by trees in limited growing spaces, and use this knowledge to design parking lots with improved environmental impacts.

Composition and Estimated Value of Selected Benefits of Trees in Parking Lots in Raleigh, NC

by
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BIOGRAPHY

I grew up in the suburbs of Washington, D.C., and learned much from public school, my parents, and playing in the woods with friends. In 1996, I combined my love of the outdoors with the need to attend public school, and enrolled in the interdisciplinary ecological magnet program at Poolesville High School. After four years of field studies and service learning projects, I was hooked. I went on to study at the University of Maryland, graduating with a B.S. in Environmental Science and Policy in 2004. When not in class, I worked as a summer camp counselor, built a trebuchet, helped clean up the Anacostia River, and served as president of a volunteer wilderness search and rescue team. I managed to keep my grades high, and was inducted into Phi Beta Kappa. After graduating, I measured trees in and around the National Mall for the National Park Service, collected bees for the U.S. Geological Survey, performed quality control on aerial photographs, and helped write environmental impact statements for the Nuclear Regulatory Commission. As a graduate student at North Carolina State University, I was selected for a national scholarship by the Garden Club of America, served as a teaching assistant for three courses, and was selected as one of ten Outstanding Graduate Teaching Assistants. I am currently working full-time as an AmeriCorps VISTA with the City of Raleigh as a Water Conservation Program Planner, and plan to attain a permanent position with the Federal government once my service is complete. I hope to continue to learn and grow while working on projects that are both useful to society and personally rewarding.

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CHAPTER 1: BACKGROUND AND SIGNIFICANCE

1.0 Parking Lots Create Adverse Impacts

Parking lots are an integral component of our transportation system, and allow access by automobile to almost every destination. This convenience is generally appreciated by motorists, who may be frustrated when inexpensive parking spaces are not available near their destination. Therefore, off-street parking is usually considered an important amenity by city governments, which typically require new development to provide enough parking to satisfy potential demand. While the positive aspects of parking lots are generally appreciated, the negative impacts are less obvious, and warrant further consideration.

Parking lots create a variety of negative environmental, social, and economic impacts. Parking lots affect water quality by increasing water temperature (Van Buren et al. 2000), stream sedimentation (Albanese & Matlack 1999), bank erosion (Hammer 1972), and levels of contaminants such as grease and oil (Stenstrom et al. 1984), nutrients (Hope et al. 2004), and carcinogenic chemicals from sealants (Mahler et al. 2005). These changes can have significant impacts downstream, both for public health (Gaffield et al. 2003) and ecosystem function (Wang et al. 2001). The pavement in parking lots contributes to the urban heat island effect (Asaeda et al. 1996, Celestian, and Martin 2004, Grimmond & Oke 1999). Parked vehicles emit hydrocarbons and nitrogen oxides (Hahn and Pfeifer 1994, Scott et al. 1999), while vehicles navigating parking lots emit a variety of air pollutants (EPA 2007). Large amounts of parking have been blamed for reducing the density of urban areas, creating an environment that is scaled to vehicles instead of people, impairing the street life and

economic vitality of the inner city, and unfairly restricting access to shopping opportunities to those who can afford vehicles (Shoup 2005, Alexander et al. 1977, Kunstler 1996, Jackson 1996, McClain 2000). Because each parking space can cost thousands of dollars to construct, parking lots may increase the costs of goods, services, taxes, and rent; additionally, some businesses have difficulty competing in areas where they are required to provide free parking (Shoup 2005).

The negative social, environmental, and economic impacts of parking lots are highest in places where parking is concentrated, but the relationship between the amount of land devoted to parking and the impacts of that land use is not necessarily linear. Rather, it has been posited that thresholds exist where the impacts change dramatically.

Stream and wetland quality begins to be impacted when a watershed exceeds 10% impervious surface, and degradation becomes almost unavoidable at 30% (Arnold & Gibbons 1996). Alexander et al. (1977) hypothesized a negative subliminal effect on people when the ground area devoted to parking in any 10 acre area approaches a threshold of 9%. This hypothesis was not tested by the authors, but originated from their observations. Environmental and social impacts may be disproportionately large in areas where parking is concentrated and exceeds these thresholds.

1.1 In the U.S., Parking is Concentrated in Urban Areas

Research conducted in a variety of methods in cities across America suggests that parking is concentrated in urban areas, with the highest density of parking in major cities and in industrial and commercial areas. An unpublished study by the RBA group (reprinted in

Edwards 1994) focused on amount of parking in downtown areas in U.S. and Canadian cities with populations between 5,000 and 68,000 people. Only private and public off-street parking spaces in the central business district were counted. Because some of these parking spaces may be in multi-story parking garages, the total footprint of parking lots in these communities cannot be calculated using these data alone. Likewise, without knowing the size of each downtown area, the percentage of the downtown area covered with parking cannot be estimated. However, these data do show a trend that the number of parking spaces in a downtown area increases with community size.

Remote sensing methods provide a more accurate avenue for assessing the amount of land devoted to parking, and have been used to assess the area devoted to parking in two suburban areas. Using high-resolution Quickbird satellite imagery, Hester et al. (2009) estimated that the amount of parking associated with commercial development occupied 5.8% of a 71.5 km^2 suburban section of Raleigh, North Carolina. Davis et al. (2009) used high-resolution aerial photographs to digitize and estimate the area of parking lots and parking decks in Tippecanoe County, Indiana, containing the city of Lafayette and Purdue University. They included all areas where off-street parking spaces were visible, including open parking lots and the top levels of six of the eight multilevel garages at Perdue University. They did not include on-street parking, parking spaces that were not visible in the photographs, areas of ingress and egress, or landscaping areas larger than one parking space in area. They estimated that parking lots covered less than 0.5% of the total area and 6.57% of the urban area in the county, and had a combined area of 5.65km^2 (1,397 acres).

This same research team also found a correlation between parking coverage and the intensity of urban development (Davis et al. 2007). They found the 2001 National Land Cover Data (NLCD) urban land use value to be the best predictor of parking coverage, and used multiple linear regression to estimate parking lot coverage in the states of Wisconsin, Michigan, Indiana, and Illinois. They estimated that parking lots covered less than .01% of the total area and 4.97% of urban areas in these states, and had a combined area of 1,260 km^2 (311,000 acres).

Larger cities appear to have the highest concentrations of parking. McPherson (2001) used aerial photography from 1992 and a dot grid to estimate that parking covered 5.6% of Sacramento. Akbari and Rose (2008) used high-resolution (0.3 to 0.5 m) aerial photographs and hundreds of randomly generated points to estimate the coverage of different surface types in seven land use categories in the cities of Chicago, Houston, Sacramento, and Salt Lake City. As with Davis et al. (2009), only parking lots and the visible top levels of parking decks were measured. On-street parking areas and parking spaces that were not visible in the aerial photo were not measured. These areas were found to cover 11% (51.1 km^2, 12,600 ac) of Salt Lake City (Akbari & Rose 2001a), 11.8% (95.2 km^2, 23,500 ac) of Sacramento (Akbari et al. 1999), 15% (360.5 km^2 , 89,080 ac) of Chicago (Akbari & Rose 2001b), and 18% (561.8 km^2, 138,800 ac) of Houston (Rose et al. 2003).

Within cities, parking may be further concentrated by land use. In Olympia, Washington, parking lots cover between 4% and 9% of residential areas, between 10% and 20% of multifamily residential areas, and between 39% and 64% of commercial areas (City of Olympia 1995). In the previously discussed studies of four cities, researchers at Lawrence

Berkeley National Laboratory found that parking covered between 2.2% and 9.9% of residential areas, between 18.6% and 29.4% of industrial areas, and between 25.7% and 34.7% of commercial areas (Akbari et al. 1999, Akbari & Rose 2001a, Akbari & Rose 2001b, Rose et al. 2003). Shopping centers have particularly high amounts of parking, and are concentrated around major roads and highways (Shoup 2003, Wolf 2009).

Together, these studies indicate a pattern in which areas with the densest concentrations of people also have the densest concentrations of parking. Almost 4 out of 5 Americans live in urban areas (U.S. Census 2009), where parking lots can cover between 5% (Davis 2007) and 18% (Akbari and Rose 2008) of the total urban area and create negative environmental, social, and economic impacts. These impacts are even higher in the commercial and industrial areas in which we shop and work, where between 18% (Akbari and Rose 2008) and 64% (City of Olympia 1995) of land is covered by parking lots. Therefore, opportunities to reduce the negative impacts of parking lots may be of interest to city governments.

1.2 Trees Create Benefits Which May Improve Parking Lots

A variety of best management practices have been suggested to reduce the negative impacts of parking lots. Such methods include engineered structures such as stormwater detention ponds and infiltration trenches, as well as nonstructural practices such as planting trees (Arnold & Gibbons 1996). The costs of parking lots which are ultimately borne by consumers, renters, and taxpayers are considerable (Shoup 2005), and installing and maintaining these modifications adds to these costs.

Economic costs of urban trees include planting, watering, mulching, pruning, and removal (McPherson et al. 2005a). Additionally, the space needed for trees to grow in parking lots represents an opportunity cost, as this area could be used for parking vehicles or to meet other needs. Trees may also have negative effects for people and the environment, as they can release VOC's and pollen; drop fruit, leaves, and branches; encourage undesirable plants and wildlife; and raise insurance rates. Many cities have determined that the public benefits of trees outweigh their costs, and passed municipal ordinances requiring trees to be planted in and around parking lots. Research has shown that the benefits of street trees can outweigh their costs (McPherson et al. 2005a, 2005b), and these assumptions may apply to trees in parking lots as well.

The costs and negative effects of trees in parking lots are important factors to be considered when determining whether or how to plant trees in parking lots, but a thorough discussion of the costs and benefits of parking lot trees lies beyond the scope of this paper. Instead, the following discussion concentrates on the benefits of trees, which are often cited by cities as reasons to require trees in parking lots. Researchers have documented multiple benefits of trees that may help to improve parking lots, including creating shade, moderating microclimate, improving air quality, and improving the appeal of these areas to people.

1.2.1 Trees Shade People and Materials

Perhaps the most recognized benefit of trees is their ability to create shade, and in some ordinances they are called shade trees (Municode.com 2009). Researchers have estimated that trees reflect or absorb approximately 80% of incoming solar radiation in a

shaded parking lot (Scott et al. 1999). The shade produced by trees absorbs ultraviolet radiation which can cause sunburns, skin cancer, and cataracts in people, and which can degrade paint and vehicle parts (Heisler & Grant 2000).

The shade created by trees can extend the amount of time between pavement resurfacing, reducing maintenance costs. McPherson and Muchnick (2005) examined the relationship between tree shade and pavement performance, and estimated the economic savings from delayed or decreased maintenance and replacement of a paved street 125 ft (38.1m) long and 35 ft (10.7 m) wide. They estimated that the time between resurfacing operations could be extended from 5 years to 6 years using 30-year-old crape myrtle (*Lagerstromia indica* L.) trees or to 12 years using 30-year-old hackberry (*Celtis occidentalis* L.) trees. The resulting estimated cost savings over a 30 year period were $829 using crape myrtles (17% reduction in resurfacing costs), and $2,900 using the larger hackberry trees (58% reduction in resurfacing costs).

1.2.2 Trees Moderate Microclimate

Trees can moderate local climate, reducing air temperatures during hot periods, retaining warmth during cooler times, and reducing wind speed. Trees create a cooler, moister microclimate by reflecting and absorbing solar radiation and transpiring water from their leaves (McPherson et al. 2005a). Trees and other vegetation on individual building sites may lower air temperatures 5°F (3°C) compared with areas outside the greenspace (McPherson et al. 2005a). Scott et al. (1999) compared summer temperatures in a parking lot shaded by trees with an unshaded lot, and found that ambient air temperature was between

0.9º F and 3.6º F cooler in a shaded parking lot, pavement was 40 º F cooler; vehicle cabin temperatures were 47 º F cooler, and fuel tank temperatures were between 3.6 º to 7.2 º F cooler. Depending on spacing and size, trees can serve as a windbreak, reducing wind speed and reducing heat loss from buildings in the winter (Heisler 1986).

1.2.3 Trees Improve Air Quality

Trees can prevent pollution formation and passively or actively remove pollutants from the air, improving air quality. In the aforementioned study of gas tank temperatures, Scott et al. (1999) found that the cooler fuel tank in the shaded car was estimated to reduce reactive organic gas emissions by 2% and nitrogen oxide gasses by 1%. While these may seem modest gains, they equal expected reductions from other control measures being implemented, such as alternative fuel stations (Scott et al. 1999).

Whether ground-level ozone forms depends on ambient temperature; thus, cooling effects of parking lot trees may help reduce ozone concentrations (McPherson et al. 2005a). Additionally, ozone and other gasses are absorbed into the leaves of trees, where they are degraded (McPherson et al. 2005a). Fine particulate matter, such as dust, ash, pollen, or smoke, is intercepted by the outside structure of leaves, where some of it is retained and washed to the ground during storms (Beckett et al. 1998). Additionally, by reducing energy demands on buildings in a city, air pollutants emitted from power generation can be reduced (McPherson et al. 2005a).

1.2.4 Trees Intercept Stormwater and Improve Water Quality

Trees can mediate the amount of water running off a parking lot, and reduce the levels of pollutants reaching streams. Sanders (1986) found that tree canopies in Dayton, Ohio lower potential runoff during a strong storm by about 7%. Xiao et al. (2000) found that the first 1 to 2 inches of rain (50-100 gallons per tree) were retained by a tree's canopy and evaporated following the rain event. Because small storms are responsible for most pollutant washout from parking lots, and the relative effect of interception is greater for small rainstorms than for large storms, trees may create a significant benefit to water quality through interception (Xiao et al. 2000). Trees can also control the role of the soil in the hydrologic cycle by reducing erosion, encouraging groundwater regeneration, and enhancing the ability of the soil to hold moisture (McPherson et al. 2005a).

By reducing the need for resurfacing, trees may reduce the toxicity of parking lot runoff. Parking lot sealants are typically based on coal-tar, and contain polycyclic aromatic hydrocarbons (PAHs) which are known carcinogens and adversely affect people, plants, and animals (Mahler et al. 2005). Parking lot sealant may be responsible for the majority of PAHs in urban streams, with sealed lots creating 65 times more PAHs than unsealed asphalt and cement surfaces (Mahler et al. 2005). Reducing chemicals like PAHs has been cited as one of the best ways to improve drinking water quality in downstream communities (Gaffield et al. 2003). Additionally, by moderating pavement temperatures, runoff from parking lots can be cooled, which may help to avoid low oxygen conditions associated with warm streams.

1.2.5 Trees Improve Human Experiences

Some observers have proposed that parking lots represent the new town squares by providing public spaces where people interact (Mayer 2005). During months of research in a small, unidentified community in Wisconsin, one observer noted that adults were seen outside only when crossing parking lots to shop or return to their cars, despite the presence of a large public park (Childress 2004). Spaces that facilitate human interaction and reflect civic ideals can be created using trees, such as outdoor rooms, gateways, groves, open squares, or lined pathways (Alexander et al. 1977, Jakle and Schulle 2004). A double row of trees with a central walkway can provide a safe and comfortable route for pedestrians, and has been recommended for use in parking lots by landscape architects (Harris 2004, Adams 2006).

Studies have illustrated a preference of people for trees in parking lots and other urban areas. Anderson and Stokes (1989) found that high levels of vegetation, whether maintained or natural, made parking areas more attractive, and well-maintained landscaping materials made people feel more secure in parking lots. Scott et al. (1999) documented an apparent preference among drivers for shaded parking spaces in California during the summer. As air temperature rose from 73º F to 100º F, the percentage of cars parked in shaded spots increased from 25% to 68%, while the percentage of cars in less-shaded spots decreased. Additionally, people may use landmarks like trees to locate their cars in parking lots (Jakle and Schulle 2004).

Wolf (2009) tested user preferences for hypothetical strip mall parking lots with different vegetation schemes. She found that people felt parking areas with mature trees were

more attractive and comfortable than areas without trees. The highest rated lot contained trees of varying sizes and species and shrubs. Customers were willing to travel significantly farther and more frequently, stay longer, and pay 8% more on average for goods in the shopping centers with trees. Trees have also been shown to increase commercial rental property values by 7% (Laverne & Winson-Geideman 2003).

1.3 Potential Benefits of Trees in Parking Lots

In addition to these well-documented benefits, there are possible benefits for which evidence of significant value is lacking, but which could be shown to be important in the future.

1.3.1 Carbon Sequestration

Urban forests have been recognized as potentially important storage sites for carbon dioxide (CO_2), the primary greenhouse gas (Rowntree & Nowak 1991, Nowak & Crane 2002). A large deciduous or evergreen tree growing in this region is estimated to assimilate 0.3 metric tons of carbon per year, more than nine times the amount assimilated by small trees (McPherson & Simpson 2000). When the energy conservation effects of trees are considered, the potential atmospheric carbon reduction of tree planting projects may be greatly increased (Rowntree & Nowak 1991, McHale et al. 2007).

1.3.2 Chemical Effects

Trees create many chemical compounds, some of which have medicinal, environmental, pesticidal or herbicidal effects. Living trees can exude chemicals which are inhaled by people, and it has been proposed that that simply being near certain trees can bring medical benefits (Beresford-Kroeger 2003). With additional research, we might better understand how the chemicals emitted by different trees affect their surroundings, and use these effects to reduce costs and increase benefits.

1.3.3 Ecological Effects

Trees play critical roles in the ecology of forests, providing food and shelter for a variety of animals, plants, fungi, and microorganisms. Wildlife is generally appreciated in metropolitan areas, but can impose significant costs from damage and may be considered a nuisance (Conover 1997). Providing habitat for "living things" is listed as one of the purposes of Raleigh's landscaping ordinance (of which the vehicular surface area landscaping ordinance is a subsection), yet the types of living things are not specified (Municode.com 2009). If people prefer certain species of plants and wildlife in parking lots, it might be possible to use trees to create sites that support these species.

1.3.4 Forest Products

When urban trees such as those in parking lots reach the end of their useful lives, they can be recycled into mulch, clean wood chips, firewood, or milled lumber, offsetting disposal costs and possibly generating income (Cesa et al. 1994, Sherrill 2003). Large urban trees may

be turned into valuable lumber products using portable bandsaws and drying kilns (Sherrill 2003). Large veneer quality sawlogs might be made from some trees, but trees with poor health or of wrong species might only be suitable for wood chips, which could be used as a mulch, as an energy source, or for other purposes. However, these benefits haven't been measured for trees in parking lots.

1.3.5 Jobs and Economic Impact

In a report for the University of Georgia, Flanders and McKissick (2007) found that landscape services in four urban counties in Georgia had a total economic impact of $1.4 billion, including $66 million in state and local taxes, and were responsible for a total of 20,969 jobs. Planting, maintaining, and removing landscaping in parking lots was not studied, but may contribute to this economic activity.

1.3.6 Environmental Justice

Most parking in the United States is free, and benefits those who are healthy and wealthy enough to drive. The costs are borne equally by those who do not drive in the form of higher costs for products and services, higher taxes, and social and environmental impacts (Shoup 2005). Some have also suggested that free parking is racist, because poorer minorities have fewer automobiles (Jackson 1996). Trees in parking lots may help to remediate these environmental injustices by providing benefits to people who do not drive, such as shading walkways and improving community aesthetics.

1.4 Urban Forest Structure Affects Benefits

The benefits created by a component of the urban forest are determined by the species, number, and size of trees used. Different species release varying amounts of pollen and VOC's, and have different aesthetic effects due to their unique form, texture, and color. Many environmental effects, including improvement of water and air quality are dependent on total leaf surface area, which is dependent on the size and number of tree canopies (McPherson et al. 2005a).

1.5 Conclusion

The negative impacts of parking lots have been demonstrated, and are highest where parking lots are concentrated. Urban areas have high amounts of parking relative to their size, meaning that a growing portion of Americans live in areas with higher levels of impacts from parking lots. Many cities require trees to be planted within and around parking lots to create benefits. There are financial costs associated with planting, maintaining, and removing trees in parking lots, and these trees may have negative impacts which are beyond the scope of this paper, but which should be carefully considered along with the benefits which are expected to be provided by these trees. Numerous studies show that trees can be effective at providing benefits which may improve parking lots, including moderating climate, creating shade, improving water quality, and creating an environment favored for human use. Additional benefits may be realized in the future with additional research or changes in policy or management. The benefits created by trees depend ultimately on the

number, size, and species used. Therefore, understanding the distribution of parking lots and the composition of trees within these lots is important for those who wish to improve this land use.

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CHAPTER 2: Composition and Estimated Value of Selected Benefits of Trees in Parking Lots in Raleigh, NC.

Abstract

Trees are often planted in parking lots to reduce the environmental and visual impacts created by these paved surfaces. I used a two-phase cluster sampling scheme to assess the composition of trees within parking lots in Raleigh, NC, USA. These parking lots contain discrete unpaved areas, called inclusions, which I classified into four types by size and shape: inclusions smaller than 1,000 ft^2 were categorized as compact "islands" or linear "slivers", and inclusions larger than 1,000 ft^2 were categorized as compact "chunks" or linear "rows". I measured more than 1800 trees in 502 inclusions within 110 parking lots to determine the overall composition of trees and how this composition varied among different inclusion types.

Raleigh's parking lots were found to contain 44,000 ± 24,000 trees (with 95% confidence). These trees were estimated to provide benefits valued at more than one million dollars annually. Inclusions containing trees that appear to have existed before construction ("preserved" inclusions) were found to have more trees, canopy, and basal area per acre than other ("designed") inclusions. Significant differences in tree composition and the proportion of trees meeting Raleigh's mature shade tree size goals were associated with the size and shape of the inclusion used. A disproportionately high number of willow oaks and trees in larger inclusions were observed meeting Raleigh's size goals for mature shade trees.

Additionally, using GIS, parking coverage was found to vary greatly between different zoning classes, with the greatest coverage in commercial and industrial areas. These results indicate that the distribution and coverage of parking lots in Raleigh, and the composition and resulting benefits of trees within these lots, may depend upon planning and design decisions made before a parking lot is constructed.

This study provides a methodology for assessing the composition of trees in a city's parking lots, which allows comparisons to be made among different types of parking lots, inclusions, and trees. While few studies have addressed the composition of trees in parking lots, this area of research has both practical and scientific value. With additional research, we may better understand how to maximize the ecosystem services provided by trees in limited growing spaces, and use this knowledge to design parking lots with improved environmental impacts.

Keywords: Urban Forestry, Inventory, Ordinance, Car Park, Automobile, Transportation, Environmental Impacts, North Carolina

Introduction

Parking lots are known to create many environmental, social, and economic impacts. Their effects on water quality include stream sedimentation and bank erosion (Albanese & Matlack 1999, Hammer 1972), and contamination with oil, grease, nutrients, and carcinogenic sealing compounds (Stenstrom 1984, Hope et al. 2004, Mahler et al. 2005).

When land cover in a watershed approaches 10% impervious surface, water quality begins to be impacted negatively, and at 30% degradation becomes almost inevitable (Arnold & Gibbons 1996). Automobiles contribute to air pollution when moving through parking lots (EPA 2007) and when parked (Hahn & Pfeifer 1994, Scott et al. 1999). The pavement in parking lots contributes to the urban heat island effect (Asaeda et al. 1996, Celestian & Martin 2004, Grimmond & Oke 1999). Large amounts of parking have been blamed for reducing the density of urban areas and subsequently impairing the street life and the social and economic character of the inner city (Shoup 2005, Kunstler 1996, Jackson 1996). Alexander et al. (1977) hypothesized that people begin to feel uncomfortable when 9% or more of any 10 acre area is devoted to parking (Alexander et al. 1977).

In the U.S., parking is concentrated in urban areas. Using remote sensing methods, Davis et al. (2009) estimated that parking lots cover less than 0.5% of Tippecanoe County, Indiana, but 6.57% of the urban area in that county. In 2007, the same researchers found a correlation between the 2001 National Land Cover Data urban development values and parking coverage. Using multilinear regression, they estimated that parking covers 0.1% of overall area and 4.97% of urban areas in the states of Wisconsin, Michigan, Indiana, and Illinois. McPherson (2001) estimated that parking lots cover 5.6% of Sacramento. Hester et al. (2009) estimated that commercial parking lots cover 5.8% of a study area in Raleigh, North Carolina. Researchers at Lawrence Berkeley National Laboratory estimated that parking lots cover between 11% and 18% of the cities of Chicago (15%), Houston (18%), Sacramento (12%), and Salt Lake City (11%) (Akbari et al. 1999, Akbari & Rose 2001a, Akbari & Rose 2001b, Rose et al. 2003).

Trees can provide a wide range of environmental and social benefits that may improve parking lots. Tree shade has been shown to reduce damaging ultraviolet rays (Heisler & Grant 2000), reduce solar degradation of pavement and the need for resurfacing (McPherson & Muchnick 2005). Trees moderate temperatures of pavement, air, and automobile cabins and gas tanks, reducing ozone precursors (Scott et al. 1999). Their canopies absorb ozone and particulate matter (Beckett et al. 1998, Nowak et al. 2006), sequester carbon dioxide (Rowntree & Nowak 1991), and intercept and retain stormwater (Xiao et al. 2000). Anderson & Stokes (1989) showed that well-maintained trees in parking lots improved peoples' perceptions of an area's comfort, attractiveness, and security. Customers preferred shaded parking spaces in a California lot during the summer (Scott et al. 1999) and were willing to pay more for goods, travel further, and stay longer in shopping centers with good tree cover in their parking lots (Wolf 2009).

Many of these benefits depend on the composition (number, size, and species) of trees used. Trees with larger canopies have greater effects on aesthetics, water quality, shading, and air quality (Schroeder et al. 2009). Additionally, larger trees have a higher benefit-to-cost ratio than smaller trees (McPherson 2005a). Species choice also affects the ability of trees to provide benefits over time, not only in determining the mature size of trees, but also in their lifespan, aesthetic characteristics, resistance to pests and diseases, and VOC and pollen emissions.

In recognition of the negative impacts of parking lots and the benefits of trees, cities like Raleigh, North Carolina have enacted municipal ordinances that specify how trees are to be grown in and around parking lots to provide aesthetic, economic, and environmental

benefits (Appendix A). However, parking lot owners and designers have considerable flexibility in fulfilling this ordinance. They may choose to preserve existing trees, if any are available, or they may plant new trees; they may choose the size and shape of the area preserved or created for trees to grow in, as long as minimum size requirements are met; and they may choose the species of tree planted, as long as a minimum number of trees are expected to reach a specified size at maturity. My goal was to better understand the composition of this portion of Raleigh's urban forest, and to determine how this composition varies with respect to the choices made during the design process. The key questions were:

1. What percentage of the study area is covered by parking lots, and how does this coverage vary among land use zones?
2. What is the overall composition (species, size, number per acre) of trees within these parking lots, and what are the implications of this structure for current and future benefits?
3. How does the composition of trees vary between inclusions that contain trees that appear to have been preserved during lot construction and inclusions that do not?
4. How does the composition of trees vary among inclusions of differing size and shape?
5. What design characteristics are associated with trees that are currently meeting Raleigh's mature shade trees goals?

Materials and Methods

Study Area

The study area consisted of the city of Raleigh, North Carolina and its extraterritorial jurisdiction, the area outside city limits over which the city has planning authority. Raleigh passed an ordinance requiring trees to be planted in and around parking lots in 1987, for purposes including air purification, stormwater retention, groundwater recharge, aesthetic and economic improvement, energy conservation, and reduction of heat and noise (Municode.com 2009).

Site Selection and Sample Design

The City of Raleigh has made publicly available a series of planimetric digital maps, including a map of the parking lots in Raleigh as they existed in 2006. I compared these maps to high-spatial-resolution (6 inch) color aerial orthophotos taken in the winter of 2006 and found that they reflected the size and shape of the parking lots in the orthophotos accurately. Areas of ingress and egress, parking spaces, the top levels of some parking decks, and loading and unloading areas were included, but areas of landscaping and other nonpaved surfaces were not included.

The City has also made available a digital map of the more than 2,400 districts, each having one of 43 zoning classifications. I used a Geographic Information System (GIS) to calculate the area in each district that was covered by parking surfaces. I calculated the total

area and area covered by parking in each zoning classification, and combined similar classifications (e.g. all Office and Institution zoning classifications).

The majority of trees in parking lots in the study area are found in discrete, nonpaved areas, such as median strips, islands, planting areas, and tree pits. To ensure clarity and develop a standard nomenclature which is needed to study parking lots (Scott et al. 1999), I refer these areas collectively as "inclusions". These inclusions were included in Raleigh's digital maps, and I extracted them using ESRI's ArcGIS 9.2. Inclusions containing buildings were removed from further consideration, and the area and perimeter of the remaining inclusions were calculated.

For each of the remaining inclusions, I calculated a compactness ratio (K), defined as $K = \frac{2\sqrt{\pi}(\text{Area})}{\text{Perimeter}}$ (Forman 1995). This ratio compares the perimeter of a shape (the denominator) to the perimeter of a circle with the same area (the numerator), and decreases from one for circular shapes toward zero for increasingly long, thin shapes. The area of each inclusion was plotted against its compactness ratio (K), revealing a clear clustering in the upper left and lower right quadrants (Figure 1). Inclusions were grouped into four types on the basis of their size and shape, called islands, rows, chunks, and slivers.

Of the 10,023 digitized parking lots, more than 8,000 (80%) did not contain inclusions. Most of these lots were small, and therefore were not required by Raleigh's ordinance to provide space for trees within the lot interior. Because the focus of this study is on the trees in the interior of parking lots, parking lots not containing at least one inclusion were assumed to contain no trees, and removed from further consideration.

For the remaining 2,007 parking lots, I calculated:

1. the total area of the parking lot, (ft^2)

2. the compactness ratio of the parking lot, defined above (K, unitless)

3. the number of inclusions in the parking lot

4. the total area of all inclusions in the parking lot, (ft^2)

5. the ratio of parking lot area per inclusion (i.e., #1 / #3)

6. the ratio of parking lot area per square foot of inclusion area (i.e., #1 / #4).

These six values were used to perform a multivariate clustering using SAS JMP 7 (SAS Institute 2007). The resulting four clusters were named according to their defining spatial characteristics, and lots were drawn from each cluster for field sampling: simple, intensive, extensive, and elongated (Table 1). A few sampled parking lots were later found to be outside the current planning area limits, and were removed from the study.

Aerial photos and field visits were used to remove inclusions that were not completely surrounded by asphalt, concrete, or gravel, that served purposes distinctly separate from those listed in the ordinance, such as equipment storage, growing and selling ornamental plants, human burial, or trash disposal; or were not publicly accessible. Inclusions in sampled parking lots that were not originally found in Raleigh's digital data, but which met all criteria above, were digitized using recent aerial photos and field measurements. In each sampled parking lot, 12 inclusions or 20% of all inclusions, whichever was greater, were sub-sampled, stratified by inclusion type. At least one of each type of inclusion present in a lot was subsampled.

Field Measurements

Field measurements commonly collected for studies of urban tree populations (Nowak 2008) were performed between October, 2008 and February, 2009. For each woody plant having a stem with a diameter greater than one inch at a height of 4.5 feet (breast height), the following measurements were collected: tree height (ft), height to crown base (ft), diameter at breast height (in), crown diameter in two perpendicular directions (ft), crown light exposure (the number of sides receiving direct sunlight exposure, on a scale of 0 to 5), and species (or genus if species was not evident). Four very large preserved inclusions, each containing hundreds of trees, were subsampled, and every tree with a diameter greater than one inch at a height of 4.5 feet within each subsampled plot was measured. Parking lots with no acceptable inclusions were removed from the study, and the estimated total population for each type of parking lot was adjusted accordingly.

Of the 501 sampled inclusions, 41 were classified as "preserved" inclusions (Figure 2). These inclusions contained at least one tree whose size, species, and location indicated that the tree was likely growing in a field or forest before the parking lot and associated buildings were constructed. Additionally, these inclusions often had high points or depressions, were elevated above the lot surface by retaining walls, contained a high density of trees, or closely resembled unmanaged forests. All other inclusions, which did not contain trees or which contained trees that were likely to have been planted during or after parking lot construction, were labeled as "designed" inclusions.

Data Analysis

Data for each species, tree, inclusion, and parking lot was imported into a database which was linked to the geographic data. Each parking lot and inclusion was weighted using the inverse probability of the lot or inclusion being drawn, and each tree was assigned the weight of its inclusion. In the four subsampled inclusions, each tree was further weighted with the ratio of the area of the inclusion to the area of all measured plots within that inclusion. I used SAS JMP 7 to analyze the composition of trees at the lot and inclusion levels. Results were considered significant at $\alpha = 0.05$, and all ranges are reported as 95% confidence intervals. Because all trees in parking lots are assumed to be in identified inclusions, the results are expected to apply to all trees in parking lots in Raleigh's planning jurisdiction.

Estimation of Benefits and Costs

The effects and values of all trees in designed inclusions in parking lots in Raleigh were calculated in two ways. First, these trees were grouped into five categories by diameter at breast height; 1"-5.9", 6"-11.9", 12"-17.9", 18"-23.9", and 24" and above. I used the National Tree Benefits Calculator (Casey Trees and Davey Tree Expert Co. 2009) to estimate the benefits of open-grown red maple (*Acer rubrum* L.) trees in Raleigh's climate zone and a park/open space land use. This tool is based on the U.S. Forest Service's STRATUM model (McPherson et al. 2005b), which was designed to estimate the benefits of street trees. The reference city for Raleigh's climate zone is Charlotte, North Carolina. Multiplying the estimated total number of trees in each diameter class by the value of the smallest diameter

red maple tree in that class yielded conservative estimates of the total amount and value of five benefits: stormwater retention, increased property value, energy demand reduction, carbon dioxide reduction, and air pollution reduction (Appendix B). This process was then repeated using the largest diameter red maple tree in each diameter class to create an upper estimate of these values. Dividing these total values by the total estimated area in designed inclusions yielded average values per acre of included space.

The second method for calculating the value of trees in designed inclusions relied on estimating the number of trees in each of four species size classes (Appendix C). I used two references (USDA 2009, Dirr 1998) to categorize each tree species as small-growing (typical mature height <30 ft), medium-growing (typical mature height between 30 and 40 ft), large-growing deciduous (typical mature height >40 ft), or large-growing conifer (typical mature height >40 ft). The U.S. Forest Service published a report estimating the average annual costs and benefits of a representative tree in each of these species size classes, growing in public sites (including both park trees and street trees) for cities in the Piedmont region (McPherson et al. 2005a). These estimates are also based on tree measurements collected in the city of Charlotte, North Carolina, and assume a 45% mortality over 40 years. If this 40 year period is considered to be the lifespan of each parking lot tree, with each mature tree being replaced with a new sapling at that time, this model provides an estimate of the average annual benefits that can be sustained over time if the current forest structure is maintained. I used these per-tree values to estimate the average annual costs and benefits of the trees in designed inclusion using the current species composition, and the potential costs and benefits if all small- and medium-growing tree species were replaced with trees in large-growing

deciduous species. This model was not used to assess the value of trees in preserved inclusions, as these inclusions contain a very high number of trees from large-growing species that are expected to die due to self-thinning within the next 40 years.

Results

In 2006, parking lots covered 5.97% (10.9 mi^2, 28.2 km^2) of Raleigh's planning area (Figure 3), and the distribution of this surface is correlated with the type of zoning class used ($r^2 = 0.33$) (Figure 4). The areas of zoning with most intense parking coverage are associated with shopping centers (27.3% of the area in these districts), business districts (23%), and neighborhood businesses (24%). Parking lots represent less than 5% of land use in multifamily residential areas, and less than 1% of land use in single family residential, conservation, and agricultural areas. Though commercial areas have the densest concentrations of parking, the largest percentage of the city's total parking lot area is located in industrial zones (33%), followed by multifamily residential (17.7%) and offices and institutions (17.4%), due to the large amount of land in these zones.

An estimated 44,000 ± 24,000 (this and future ranges are reported with 95% confidence) trees are currently growing within the interior of parking lots in Raleigh, representing at least 60 different tree species. Of these, 18,000 ± 7,600 trees are in designed inclusions, and 26,000 ± 23,000 trees are in preserved inclusions. This is a fraction of a percent of the 17 million ± 7.4 million trees estimated to be growing within the entire study area (Unpublished Data, 2009). Extensive lots contained significantly more trees per lot than

the other three classes of lots ($p < 0.05$), and there were no significant differences in total trees per lot among the remaining three lot types. No significant differences were found in the number of trees per square foot of inclusion space among the four lot classes. Of the species identified, 46 species were native to the study area and represent a mix of upland and lowland species, including evergreens and deciduous species. An estimated 5,800 trees, or 31% of trees in designed inclusions, represent 14 species that are not native to the area. Crape myrtle (*Lagerstromia indica* L.) was the most common non-native species, representing almost half of non-native trees.

The trees in designed inclusions are estimated to create hundreds of thousands of dollars in ecosystem services each year (Table 2). Using tree diameter class, the value of the annual benefits created by these trees is estimated at between $1.1 million and $2.4 million. Using species composition and assuming a 45% mortality rate, the value of the average annual benefits of trees in designed inclusions over a 40-year period is estimated at $1.5 million. Average annual maintenance and planting costs over this period are estimated at $470,000, and average annual net benefits are estimated at $1.1 million. If all small-growing and medium-growing trees were replaced with large-growing deciduous trees, average annual net benefits would increase to $1.4 million.

Significant differences in tree composition were associated with the origin, size, and shape of the inclusion used. The composition of trees in preserved inclusions was significantly different from that in designed inclusions (Table 3). The majority of trees in preserved inclusions had no direct sunlight exposure, while trees in designed inclusions had direct sunlight exposure on all sides. Preserved inclusions had more trees, basal area, and

canopy per area than designed inclusions, and differed in dominant species and diameter distribution (Figure 5). Tree composition also differed significantly among inclusions in different size and shape classes. Among designed inclusions, significant differences in composition were found between rows and islands, between slivers and chunks, and between slivers and rows (Table 4). Among preserved inclusions, significant differences in composition were found between islands and chunks and between islands and rows (Table 5).

The probability of a tree in a designed inclusion having met Raleigh's size goal for mature shade trees in parking lots is related to the species of tree used, and the size and shape of inclusion used. Raleigh's ordinance specifies that shade trees planted to satisfy the requirements of the parking lot landscaping ordinance should be of a species that is expected to reach a height of 35 feet or more and a canopy spread of 30 feet or more at maturity (Municode.org 2009). In designed inclusions, the proportion of trees meeting this size differed significantly among red maples, willow oaks, and all other species. ($\chi^2 = 398.5$, df = 2, $p < 0.001$). Of the trees observed in designed inclusions, 1% of red maples (3 / 362), 52% of willow oaks (123 / 234), and 6% of all other species (36 / 638) had reached the size specified in the ordinance. The proportion of trees meeting this goal also differed significantly among the four classes of designed inclusions ($\chi^2 = 36.9$, df = 3, $p < 0.001$). None of the trees observed in designed slivers (0 / 38), 6% of trees observed in islands (21 / 364), 16% of trees observed in rows (110 / 681), and 21% of trees observed in chunks (32 / 151) were successful in meeting Raleigh's goal.

Discussion

Raleigh's overall parking cover is comparable to values reported for other urban areas in the U.S. (Davis et al. 2009, McPherson 2001), but far less than that of larger cities (Akbari et al. 1999, Akbari & Rose 2001a, Akbari & Rose 2001b, Rose et al. 2003), and, as in other cities, is distributed unevenly across land uses. Raleigh's residential areas had the lowest coverage of parking, (2.1% overall average); industrial areas had a moderate coverage (18.9%); and commercial/service areas had moderate to high coverage (ranging from 14.7% for office/institute to 27.3% for shopping centers, for an overall average of 18.0%). Researchers at Lawrence Berkeley National Laboratory reported similar values for parking coverage by land use in four major cities, where parking lots covered 2.2% to 9.9% of residential areas, 18.6% to 29.4% of industrial areas, and 25.7% to 34.7% of commercial/service areas (Akbari et al. 1999, Akbari & Rose 2001a, Akbari & Rose 2001b, Rose et al. 2003). These studies indicate that parking coverage may be similar in a variety of cities across the United States.

Using two models, the value of the benefits provided by trees in Raleigh's parking lots was estimated at more than one million dollars per year. These values are similar to those estimated for trees in Sacramento's parking lots. McPherson (2001) estimated that the 93,700 trees in Sacramento's lots produced annual benefits worth $699,000, which were projected to increase to $1.8 million after 15 years of growth. Of the benefits modeled for this climate zone, stormwater retention and aesthetics are the most valuable. If all small-growing and medium-growing trees in designed inclusions were replaced with large-growing trees, annual

net benefits over a 40-year period could be increased by as much as 30%, assuming that inclusions are capable of supporting such trees. Additional benefits could be created by replacing shrubs with trees and planting additional trees in inclusions with sufficient space.

However, it is clear that trees alone cannot possibly offset all of the negative impacts created by parking lots. Approximately 80% of parking lots in the study area contain no trees within their interiors, and inclusions in most lots are spaced so far apart that complete canopy coverage is unattainable. Of the modeled benefits, stormwater retention appears to be the most valuable, yet the 70 million gallons of stormwater estimated to be retained by trees in designed inclusions is less than 1% of the 8.6 billion gallons which are estimated to fall on Raleigh's parking lot surfaces annually (Appendix D). The value trees add to the aesthetic appeal of Raleigh's parking lots are difficult to quantify, but that appeal would likely be significantly lower without trees. Other benefits of these trees, including effects to reduce energy use, air pollution, and carbon dioxide, are relatively small when compared with other potential mitigation measures. For instance, if conventional photovoltaic solar panels were installed to cover an area of direct sunlight equal to the area of all parking lot surfaces in the study area, not including the area in inclusions, the energy generated annually would be equal to that produced by an 800- to 1,200-megawatt power plant (Appendix E). If this energy were used to reduce demand for petroleum or coal-fired electricity, these panels would be many times more effective at balancing energy needs and reducing air pollution and offsetting carbon dioxide emissions than the trees currently growing in Raleigh's parking lots. Therefore, inclusions containing trees should be not be viewed as a panacea for the negative impacts of parking lots, but should be part of a comprehensive approach to improve

parking lots in this area, which may include other measures, such as rain gardens, solar energy collection systems, green roofs, and pervious paving materials.

When a new parking lot is being constructed, the decision to preserve existing trees (if any are available), or to clear the area and plant new trees appears to result in two very different compositions of trees, with different levels of benefits in the short term. Because large trees provide more benefits than smaller trees (Schroeder et al. 2009), preserving existing trees may immediately provide high levels of environmental benefits, while saplings in designed inclusions may take decades to reach the same size. Research indicates it may be more cost-effective for builders to preserve trees when constructing new homes than to plant new trees, as the increased costs of preserving trees can be less than the increase in home sales price (Seila & Anderson 1982), and this may hold true for properties with parking lots as well. Raleigh's ordinance allows preserved trees to count towards the requirements of the parking lot landscaping ordinance, and other cities should consider having similar clauses in their ordinances.

Although preserved islands were found to contain more basal area and canopy area per square foot of included area than preserved rows or chunks, preserving groups of trees in larger inclusions may be more beneficial in the long term. Islands are an attractive option for preserving trees, as designers can use them to preserve large trees individually or in small groups using small areas of land. In some cases, pavement or gravel reached nearly to the tree's trunk, resulting in a very small amount of land devoted exclusively to the tree. However, many factors should be considered when determining how many trees and how much space to preserve, including the effect building a parking lot will have on the tree's

health, the tree's projected lifespan, and the ability for other trees to fill the space if the preserved tree were to die. Larger areas can support a mix of young and old trees to ensure a constant supply of large trees over time. Large preserved inclusions may also function differently as habitats for wildlife, and I observed large preserved chunks being used as small parks by people in residential parking lots.

Two different approaches to urban forest management appear to be responsible for the difference in composition of trees in designed and preserved inclusions, and each has positive and negative aspects. While the open spacing of trees in designed inclusions is aesthetically pleasing, ensures enough light and growing space for each tree, and requires few trees to be planted, the greater density of trees in preserved inclusions encourages fast growth, straight form, and rapid canopy closure with minimal human intervention. A hybrid approach, which might generate more environmental benefits, would be to start with a high density of large-growing trees per area and periodically remove poorly formed, unhealthy, or overstocked trees to provide the remaining healthy trees with enough resources needed for optimal growth. This is commonly done in hardwood plantations, where one tree is typically planted per 100 ft^2 (9.3 m^2) of growing space (NCDFR 2004), instead of one tree per 350 ft^2 (33 m^2), as currently required by Raleigh's ordinance. This process would be more economically feasible if inexpensive seedlings were used instead of the larger, more expensive saplings which are commonly planted in parking lots. Some of the trees removed in this way could be used to create wood products to offset management costs (Cesa et al. 1994). The type and value of such wood products would depend upon the species, size, and quality of trees used.

While designed islands are the most common inclusions in the study area, larger trees are growing in rows. Trees in designed rows were significantly larger in basal area and canopy area than trees in designed islands, and a greater percentage of trees in rows met Raleigh's goal for mature shade trees. The larger size of trees in rows could be due to numerous factors, including differences in tree density, species choice, tree age, use of irrigation, or fertilizer applications. I suspect that it may be due to differences in the space available for healthy root growth (Smiley et al. 2006, Celestian & Martin 2005). Wolf (2009) recommends against narrow plantings in parking lots, and suggests larger spaces for trees. Roots have difficulty growing in the hot, dry, compacted soil underneath the lot pavement (Celestian and Martin 2005). Rows are, by definition, larger than islands. In a long row, roots can grow at least in one direction without interruption, while tree roots in islands may quickly reach the end of the inclusion. The reasons for the differences in forest structure between designed rows and designed islands are not clear but suggest avenues for future research. Parking lots constructed for college campuses or public facilities could be sites where the effects of growing space, tree species, or other factors are carefully tested.

There are additional benefits to planting trees in rows in parking lots, which should be considered when designing new lots. Managers can control the spacing of trees by removing unwanted trees to provide additional growing space for exceptional trees. Removing trees in this way can help to preserve forest health and to create wood products. Shade from a single tree creates a patch of shade that moves across the lot over time, but a row of mature tree canopies can shade an aisle of parking spaces and lanes throughout the day. This would help to extend pavement life (McPherson & Muchnick 2005) and reduce VOC emissions from

fuel tanks (Scott et al. 1999). Cars usually park in rows, and a walking path can be designed along a row of trees to create a route that is more comfortable and safer than crossing the open spaces between islands. Wide, gently sloping, vegetated ditches known as bioswales are also compatible with the long shape of rows. These bioswales can serve multiple purposes, helping to control stormwater while supporting attractive vegetation (Wolf 2009).

When a designed inclusion is constructed, the designer must decide not only the size and shape of the inclusion to use, but also which species of trees to plant within this space. The proportion of observed trees in designed inclusions meeting Raleigh's goals for mature shade trees differed markedly between the two most common species, red maple and willow oak. A disproportionately small proportion (1%) of red maples observed in this study met the mature shade tree goal. In contrast, more than half of observed willow oaks met this goal. The proportion of trees meeting this goal from all other species, including trees representing species which cannot meet this goal, was significantly higher than red maples but significantly lower than willow oaks. These differences may be due to differences in age, growth rate, survival, or other factors. Tree health may also be a contributing factor, as many red maples exhibited severe trunk decay similar to that described for maples along streets in cities in New York (Luley et al. 2009), while all but the largest willow oaks had no similar problems. Many studies recommend that a single species comprise no more than 5% to 30% of an urban street tree population to reduce the threat of damaging pests or diseases (Raupp et al. 2006). Although willow oaks appear to be an excellent choice for parking lots in the study area, they should not be used exclusively.

Conclusions

This study provides a methodology for assessing the composition of trees in parking lots, and how this composition varies between different types of trees, inclusions, and parking lots. This research shows that parking lots in a Southeastern U.S. city may contain tens of thousands of trees, representing a unique and interesting component of the urban forest. Using two different methods, I estimated that the current benefits created by the trees planted in Raleigh's parking lots could be valued at more than $1 million annually. These benefits may be increased by replacing small-growing species with large-growing species, where feasible. However, parking lots cover more than 10 square miles of area in Raleigh, and it is clear that only a fraction of the environmental impacts created by these parking lots are offset by the trees growing within their interiors. Other measures, such as solar energy systems or vegetated bioswales, may help to further reduce these impacts, and may be particularly important in commercial and industrial zones where parking is most concentrated. Additional research regarding the specific costs and benefits of parking lot trees, particularly the social and ecological benefits, is needed.

The composition of trees in parking lots is largely explained by the origin, size, and shape of the inclusions in which these trees are growing. Inclusions containing trees which appear to have been growing in a field or forest before lot construction are quite different in composition from those in which new trees were planted. Additionally, significant differences in tree composition and proportion of trees meeting Raleigh's mature shade tree size goals were associated with the size and shape of the inclusion used.

While few studies have addressed the composition of trees in parking lots, this area of research has value for lawmakers, urban foresters, and parking lot designers. With additional research, we may better understand how to maximize the ecosystem services provided by trees in limited growing spaces, and use this knowledge to design parking lots with improved environmental impacts.

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Table 1: “Simple”, “Intensive”, “Extensive”, and “Elongated” Lots.

Type	Description	Number of Lots Sampled	Estimated Number of Lots in Study Area
Simple	Small size, average in size and number of inclusions	46	908
Intensive	Small size, more inclusions or larger inclusions	22	270
Extensive	Large size, compact shape	14	56
Elongated	Low compactness, large size	28	409
Total		110	1643

Table 2: Estimated Value of Annual Benefits Provided by Trees in Designed Inclusions

	Estimate of current annual benefits using smallest diameter in diameter class	**Estimate of current annual benefits using largest diameter in diameter class**	**Estimate of average annual benefit of trees over a 40 yr period using species size class (does not include preserved trees)**
Gallons of Stormwater Retained	36 million	94 million	70 million
Aesthetics (Increased Property Value)	$380,000	$900,000	$570,000
Energy Savings (Kwh)	1.2 million	2.9 million	1.4 million
Carbon Sequestered or Avoided (lbs)	6.0 million	14 million	5.2 million
Total Value of Annual Benefits	$1.0 million	$2.4 million	$1.5 million total, $1.1 million net
Average Value of Annual Benefits per Acre	$3,500	$8,500	$6,700 total, $4,700 net

Table 3: Comparison of Forest Composition in Preserved and Designed Inclusions

	Preserved Inclusions (n = 41)	**Designed Inclusions (n = 460)**
Top 10 Species or Genera	Sweetgum (39%) Loblolly Pine (16%) Shortleaf Pine (9%) Eastern Red Cedar (7%) Sourwood (5%) White Oak (5%) Red Maple (4%) Northern Red Oak (2%) Black Cherry (2%) Black Oak (2%)	Red Maple (27%) Willow Oak (17%) Crape Myrtle (11%) Northern Red Oak (8%) Lacebark Elm (4%) Holly Spp. (3%) Callery Pear (3%) American Holly (2%) Japanese Zelkova (2%) Waxmyrtle (2%)
Mean Basal Area per Acre	208 ± 29 ft^2	58 ± 8 ft^2
Mean Canopy Area Per Inclusion Area	165 ± 34%	82 ± 10%
Mean of Mean Tree Height per Inclusion	45 ± 4 ft	25 ± 1 ft
Mean Trees per Acre of Inclusion Area	327 ± 51 trees per acre	135 ± 15 trees per acre

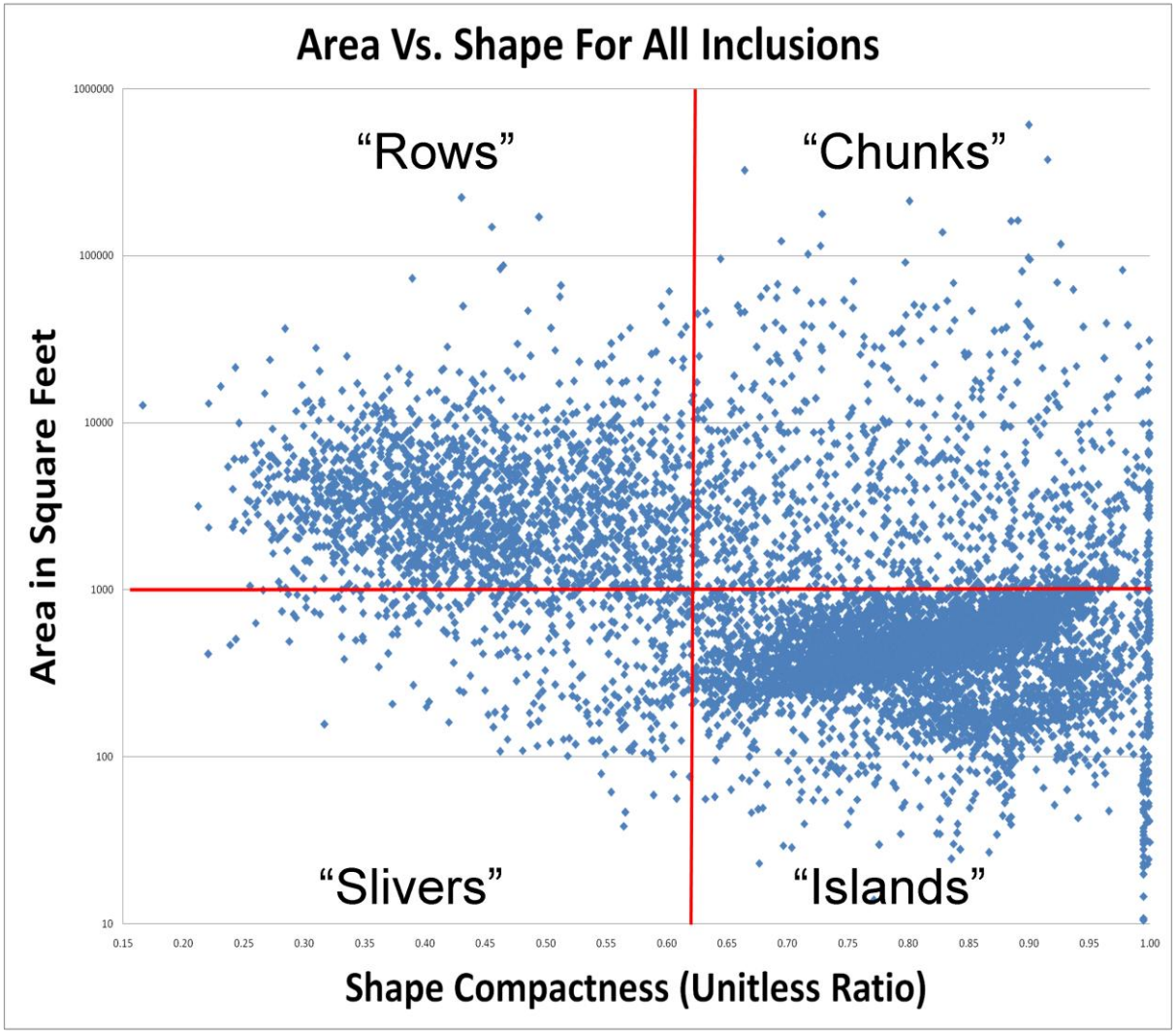
All ranges are reported with 95% confidence.

Table 4: Pairwise Comparison of Composition Among Four Classes of Designed Inclusions, Following Significant One-way ANOVAs.

	…than chunks.	**…than islands.**	**…than rows.**
Islands have…	No significant differences	**X**	**X**
Rows have…	No significant differences	Greater canopy per tree (p=0.0027) (rows=405 ft^2, islands=275 ft^2), Greater mean basal area per tree (p=0.0008) (rows=0.71 ft^2 , islands=0.44 ft^2), Fewer trees per area (p=0.0001) (rows=81 trees per acre, islands=154 trees per acre)	**X**
Slivers have…	Smaller mean tree height (p=0.0019) (slivers=16.5 ft, chunks=28.5 ft)	No significant differences	Smaller mean tree height (p=0.0024) (slivers=16.5 ft, rows=26.9 ft)

Table 5: Pairwise Comparison of Composition Among Three Classes of Preserved Inclusions, Following Significant One-way ANOVAs.

	…than chunks.	**…than islands.**
Islands have…	Greater canopy per area ($p<0.0001$) ($islands=3.21\ ft^2$ per ft^2, $chunks=1.09\ ft^2$ per ft^2), Greater basal area per area ($p<0.0001$) ($islands=390\ ft^2$ per acre, $chunks=150\ ft^2$ per acre)	**X**
Rows have…	No significant differences.	Less canopy per area ($p=0.0007$) ($rows=1.55\ ft^2$ per ft^2, $islands=3.21\ ft^2$ per ft^2), Less basal area per area ($p<0.0001$) ($rows=185\ ft^2$ per acre, $islands=390\ ft^2$ per acre)



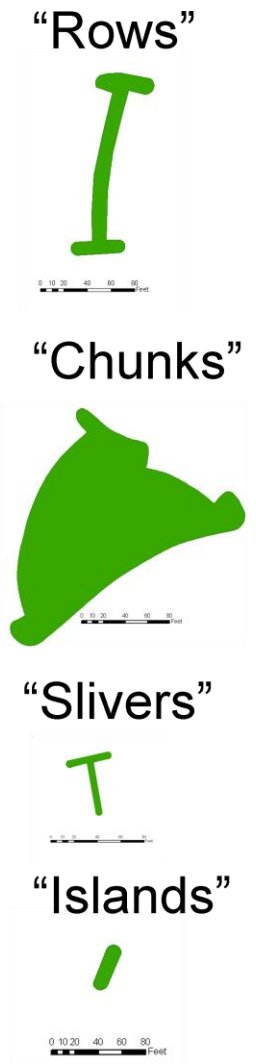


Figure 1. Inclusions by Area and Shape



Designed islands with single trees and decorative shrubs. (Photo courtesy of George Hess)



A *designed row* containing mature willow oaks. Although large, these trees were intentionally planted in the early 1960's.



These pines and hardwoods appear to be the same age as trees in nearby forests. When a parking lot was built around these trees, a *preserved chunk* was created.

Figure 2: Examples of Inclusions in Parking Lots

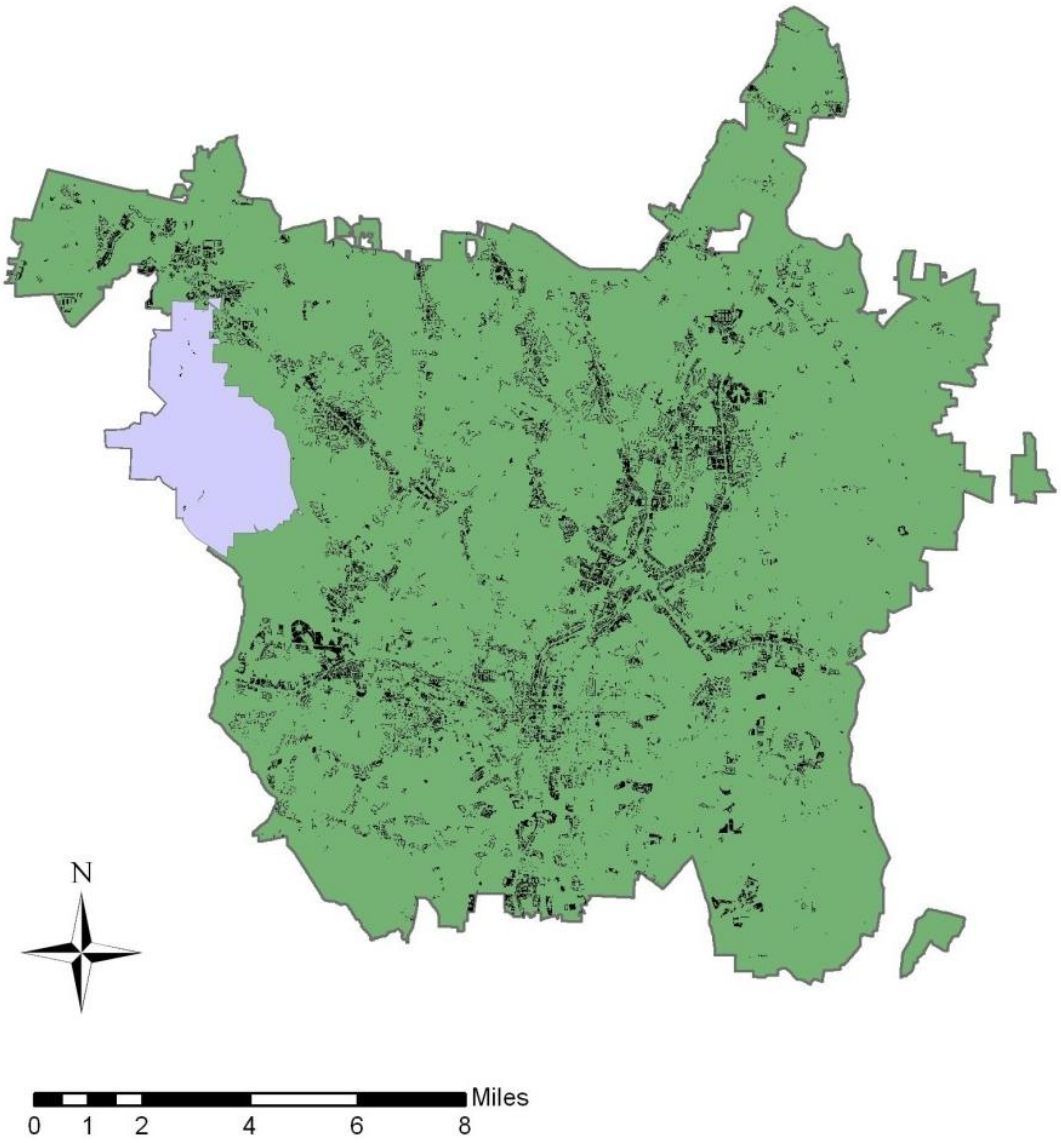


Figure 3: Map of Parking Lots in the Study Area. Parking lots cover approximately 10.9 mi^2 (28.2 km^2). For comparison, Umstead State Park (8.5 mi^2, 22.0 km^2) is shaded in blue.

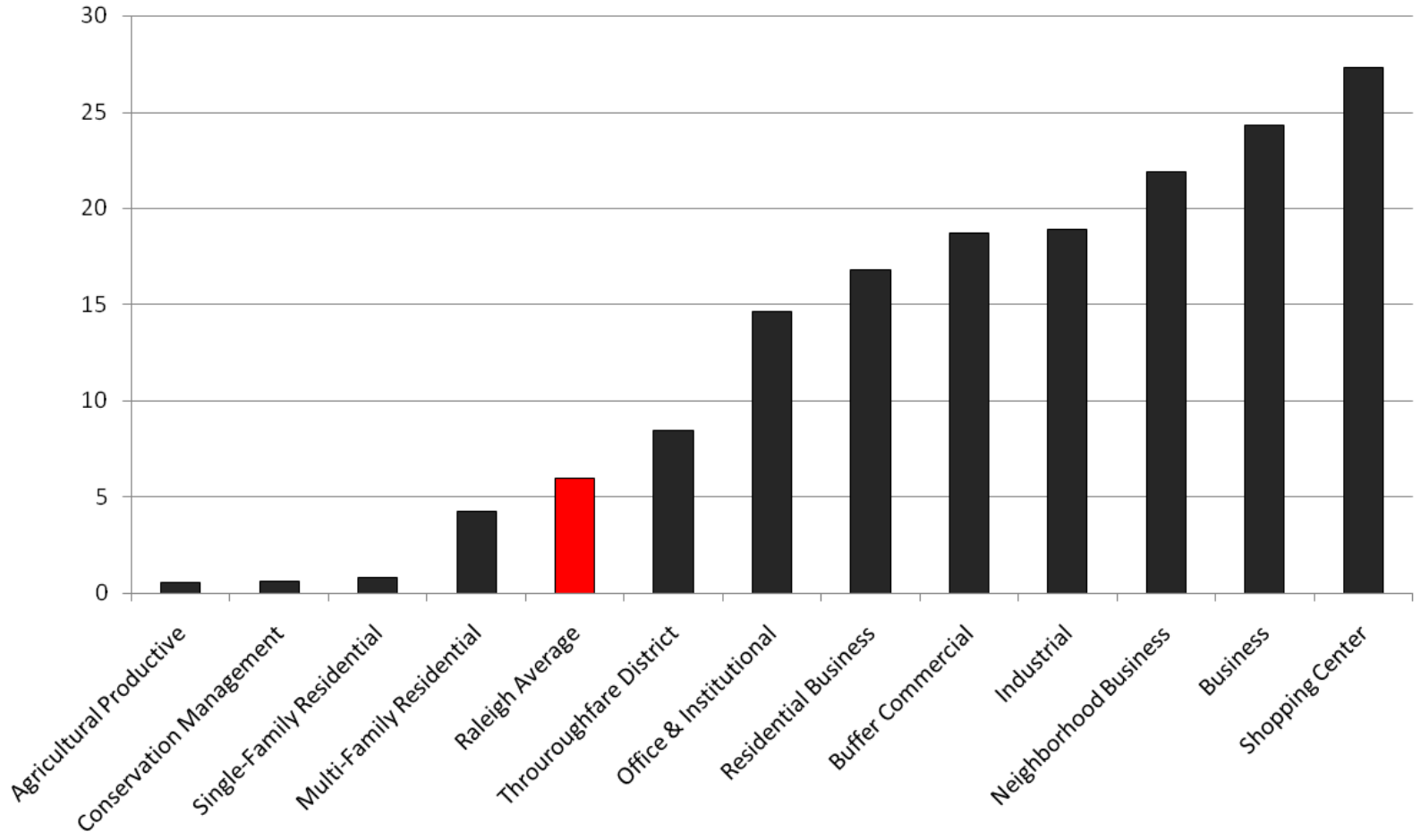


Figure 4: Percentage of Surface Area Covered in Parking Lots in Raleigh, NC by Zoning Class

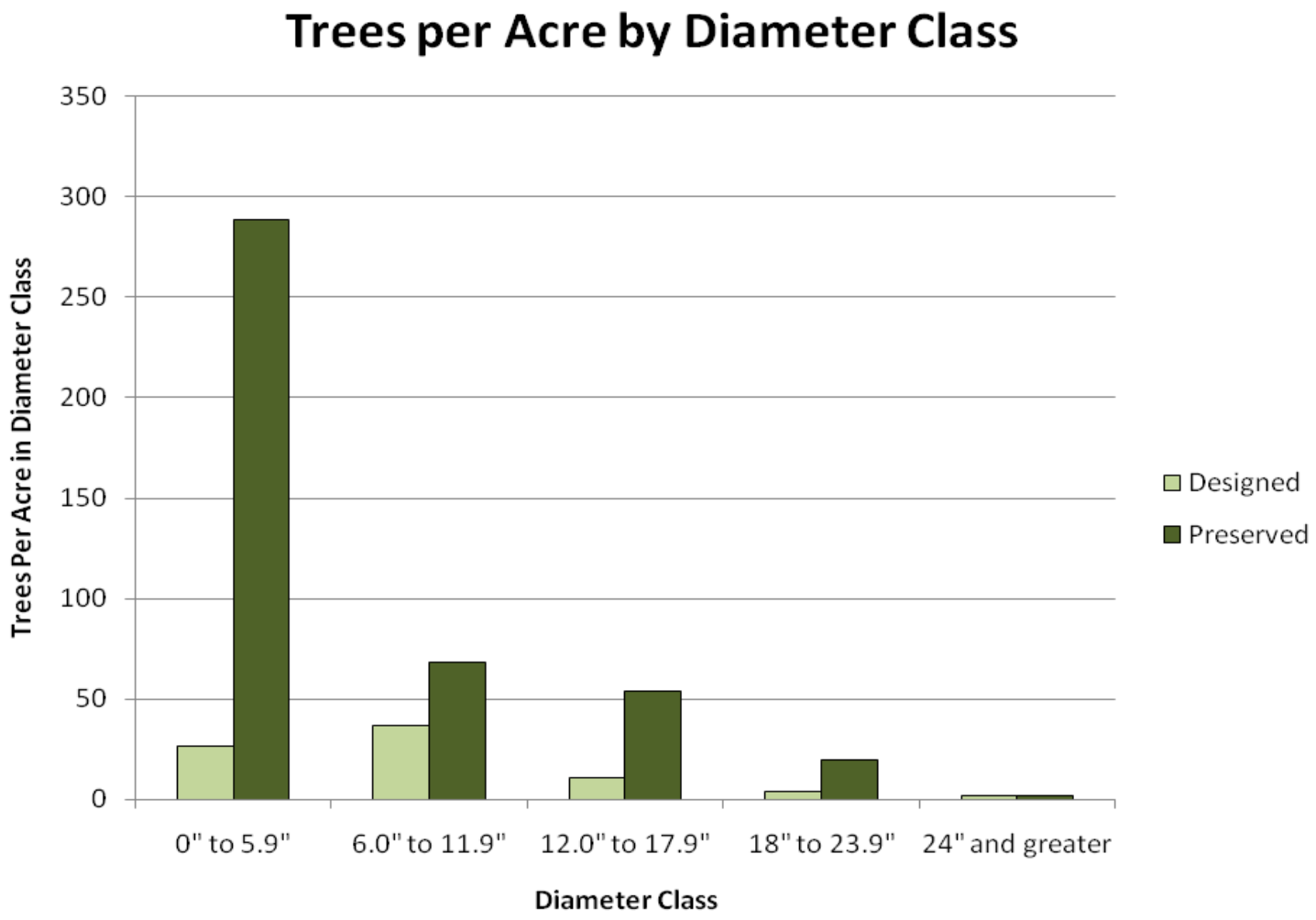


Figure 5: Estimated Density of Trees by Diameter Class and Inclusion Type

APPENDICES

Appendix A: Intent and Purposes of Raleigh's Landscaping and Vehicular Surface Area Landscaping Regulations

Source: Municode.org, accessed August 12, 2009

Sec. 10-2082. REQUIRED LANDSCAPING REGULATIONS; INTENT AND PURPOSES.

The City Council of the City of Raleigh finds that Raleigh is blessed with a diverse and abundant cover of trees and vegetation and that such cover is of general aesthetic value to the City and that the ecological diversity and richness of the City makes it a desirable place for residents, owners, and visitors alike; and that the appearance of Raleigh from the public ways contributes ecologically and aesthetically to the growth and economic prosperity of the City; and also, that Raleigh is known at "The City of Oaks" and the flag of the City and the City seal with its oak trees are symbols of Raleigh's pride in its natural heritage; and also that the growth and development attracted to the City of Raleigh, because of its natural beauty, oftentimes requires the removal of trees and other plant material, thereby contributing to the depletion of a most valuable natural resource, therefore it is necessary to protect, preserve and restore this valuable asset. The City Council declares the purposes and intent of this ordinance to be as follows:

(a) To aid in stabilizing the environment's ecological balance by contributing to the processes of air purification, oxygen regeneration, groundwater recharge, and stormwater runoff retardation, while at the same time aiding in noise, glare and heat abatement; and

(B) TO ENCOURAGE THE PRESERVATION OF EXISTING TREES AND VEGETATION; AND

(C) TO ASSIST IN PROVIDING ADEQUATE LIGHT AND AIR AND IN PREVENTING OVERCROWDING OF LAND; AND

(D) TO PROVIDE VISUAL BUFFERING AND ENHANCE THE BEAUTIFICATION OF THE CITY; AND

(e) To safeguard and enhance property values and to protect public and private investment; and

(f) To preserve, protect and restore the unique identity and environment of the City of Raleigh and preserve the economic base attracted to the City of Raleigh by such factors; and

(g) To conserve energy, and to protect the public health, safety and general welfare; and

(H) TO PROVIDE HABITAT FOR LIVING THINGS THAT MIGHT NOT OTHERWISE OCCUR TO BE FOUND IN URBAN AND SUBURBAN ENVIRONS.

(ORD. NO. 799-TC-267, TC-21-85 §1, 6-3-86)

Sec. 10-2082.6. VEHICULAR SURFACE AREA LANDSCAPE REGULATIONS.

(a) Intent, Purposes, and Application.

(1) Intent.

It is the intent of this section to modify and reduce the deleterious visual, environmental and aesthetic effects of existing and proposed vehicular surface areas. The landscape requirements herein have been developed to:

a. filter and reduce the glare of headlight and reflected sunlight from parked automobiles onto the public street rights-of-way and;

b. separate the public from the ill effects of fumes and dust and;

c. visually modify the appearance of parking areas and vehicular surface areas, to encourage the construction of such necessary areas in a manner that more closely follows the existing natural contours of the land and;

d. distribute planting areas around and within the parking area and;

e. modify the rate of stormwater runoff and increase the capability of groundwater recharge in urbanizing areas and;

f. provide shade, noise attenuation, filtering the air of particulate and gaseous pollutants and other beneficial environmental effects to the microclimate and;

g. prevent the overcrowding of land and;

h. break the visual blight created by large expanses of vehicular surface areas.

(Ord. No. 499-TC-349, §13, TC-15-89, 3-7-90)

Appendix B: Calculation of Annual Benefits of Trees in Designed Inclusions Using Diameter

Value of an Open-Grown Red Maple Tree in a Parks/Open Space Environment (from Casey Trees and Davey Tree Expert Co. 2009)

Tree Diameter	1”	6”	12”	18”	24”	30”	36”	45”
Stormwater (gallons per tree)	21	524	2,333	4,950	8,028	11,263	14,386	18,365
Property Value ($ per tree)	$0	$10	$25	$39	$50	$54	$51	$31
Energy Savings (kwh per tree)	0	24	80	140	201	261	326	427
CO_2 (lb per tree)	27	108	338	658	1052	1,497	2,012	2,963
Total Value ($ per tree)	$1	$20	$65	$117	$169	$217	$258	$297

Estimated Number of Trees by Diameter Class

Tree Diameter Class	0" to 5.9"	6.0" to 11.9"	12.0" to 17.9"	18" to 23.9"	24" to 29.9”	30” to 35.9”	36” to 45”	Total
Designed	6,015	8,333	2,401	995	270	150	43	18,208
Preserved	17,008	4,052	3,190	1,162	101	29	8	25,549
Total	23,023	12,384	5,591	2,157	371	179	51	43,758

Estimated Acreage by Inclusion Type

Type	Total Acres
Designed	226
Preserved	59
Total	285

Estimated Total Annual Values for Trees in Parking Lots using Smallest Diameter in each Class

Tree Diameter	0" to 5.9"	6.0" to 11.9"	12.0" to 17.9"	18" to 23.9"	24" to 29.9"	30" to 35.9"	36" to 45"	Total	Total/Ac
Stormwater (gallons)	483,486	6,489,474	13,043,752	10,676,196	2,981,886	2,019,737	740,365	36,434,897	127,842
Property Value ($)	$0	$123,845	$139,774	$84,115	$18,572	$9,684	$2,625	$378,615	$1,328
Energy Savings (kwh)	0	297,228	447,278	301,953	74,659	46,804	16,777	1,184,699	4,157
CO_2 (lb)	621,625	1,337,525	1,889,751	1,419,179	390,750	268,450	103,546	6,030,826	21,161
Total Value ($)	$23,023	$247,690	$363,414	$252,346	$62,773	$38,914	$13,278	$1,001,437	$3,514

Estimated Total Annual Values for Trees in Parking Lots using Largest Diameter in each Class

Tree Diameter	0" to 5.9"	6.0" to 11.9"	12.0" to 17.9"	18" to 23.9"	24" to 29.9"	30" to 35.9"	36" to 45"	Total	Total/Ac
Stormwater (gallons)	12,064,138	28,893,023	27,675,341	17,314,848	4,183,480	2,579,769	945,142	93,655,742	328,617
Property Value ($)	$230,232	$309,612	$218,048	$107,840	$20,058	$9,146	$1,595	$896,531	$3,145
Energy Savings (kwh)	552,556	990,759	782,737	433,518	96,945	58,460	21,975	2,936,950	10,305
CO_2 (lb)	2,486,502	4,185,959	3,678,864	2,268,961	556,039	360,802	152,489	13,689,615	48,034
Total Value ($)	$460,463	$804,992	$654,144	$364,500	$80,602	$46,266	$15,285	$2,426,252	$8,513

Appendix C: Calculation of Annual Benefits of Trees in Designed Inclusions Using Species Size Class

Average Annual Values for Four Representative Trees Over a 40-year Period (from McPherson et al. 2005a)

Representative Species	Species Size Class	Stormwater Retention (gal)	Energy Savings: Cooling (kwh)	Energy Savings: Heating (kwh)	CO_2 Sequestered or Avoided (lbs)	Air Pollutants Removed (lbs)
Flowering Dogwood (*Cornus florida*)	Small	1,265	44	278	168	0.98
Southern Magnolia (*Magnolia grandiflora*)	Medium	2,566	53	298	128	0.83
Red Maple (*Acer rubrum*)	Large Deciduous	4,778	89	415	340	1.37
Loblolly Pine (*Pinus taeda*)	Large Conifer	3,888	66	337	227	-2.23

Average Annual Values for Four Representative Trees Over a 40-year Period contd. (from McPherson et al. 2005a)

Species Size Class	Value of Stormwater Retention	Aesthetic Value (Increased Property Value)	Value of Energy Savings: Cooling	Value of Energy Savings: Heating	Value of CO_2 Sequestered or Avoided	Value of Air Pollutants Removed	Total Value of Benefits	Total Costs	Net Benefits
Small	$12.52	$7.29	$3.36	$2.91	$1.26	$3.75	$31.09	$24.26	$7.00
Medium	$25.40	$13.44	$3.99	$3.12	$0.96	$0.61	$47.52	$23.80	$24.00
Large Deciduous	$47.30	$41.02	$6.74	$4.34	$2.55	$3.97	$105.92	$26.89	$79.00
Large Conifer	$38.49	$23.08	$4.98	$3.53	$1.71	-$18.79	$53.00	$24.66	$28.00

Estimated Trees in Each Size Class

Species Size Class	Trees in Class
Small	3873
Medium	928
Large Deciduous	12506
Large Conifer	808
Unknown	73

Estimated Average Annual Benefits of Trees in Designed Inclusions in Study Area Over a 40-year period

	Stormwater Retention (gal)	Energy Savings: Cooling (kwh)	Energy Savings: Heating (kwh)	CO_2 Sequestered or Avoided (lbs)	Air Pollutants Removed (lbs)
Small	4,899,345	170,412	1,076,694	650,664	3,796
Medium	2,381,248	49,184	276,544	118,784	770
Large Dec.	59,753,668	1,113,034	5,189,990	4,252,040	17,133
Large Con.	3,141,504	53,328	272,296	183,416	-1,802
Total	70,175,765	1,385,958	6,815,524	5,204,904	19,897

Estimated Value of Average Annual Benefits and Costs of Trees in Designed Inclusions Over a 40-Year Period

	Value of Stormwater Retention	Aesthetics (Increased Property Value)	Value of Energy Savings: Cooling	Value of Energy Savings: Heating	Value of CO_2 Sequestered or Avoided	Value of Air Pollutants Removed	Total Value of Benefits	Total Costs of Planting and Maintaining Trees	Net Benefits
Small	$48,490	$28,234	$13,013	$11,270	$4,880	$14,524	$120,412	$93,959	$27,111
Medium	$23,571	$12,472	$3,703	$2,895	$891	$566	$44,099	$22,086	$22,272
Large Dec.	$591,534	$512,996	$84,290	$54,276	$31,890	$49,649	$1,324,636	$336,286	$987,974
Large Con.	$31,100	$18,649	$4,024	$2,852	$1,382	-$15,182	$42,824	$19,925	$22,624
Total	$694,695	$572,351	$105,030	$71,294	$39,043	$49,556	$1,531,970	$472,257	$1,059,981
Total/Acre							$6,779	$2,090	$4,690

APPENDIX D: An Estimation of Annual Stormwater Falling on Parking Lots in Raleigh, NC.

Using data provided by the city of Raleigh, it was estimated that parking lots covered 10.9 square miles in Raleigh in 2006. An inch of rain falling on this surface would amount to 190 million gallons of water. Raleigh receives an average of 45.19 inches of rain per year (SERC 2009). Therefore, assuming that parking lot coverage is accurate and applicable at the current time, approximately 8.6 billion gallons of water fall annually on Raleigh's parking lots. This is equal to approximately half of the 17.5 billion gallons of water processed by Raleigh's water treatment plant in 2006 (City of Raleigh 2009).

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APPENDIX E: An Estimation of Potential Electricity Generation by Conventional Solar Panel Arrays Above Parking Lots in Raleigh, NC

A square meter of surface in Raleigh is exposed to approximately 4 to 6 kilowatt-hours of solar radiation each day on average (EIA 2005). A single-crystal photovoltaic module has an average energy efficiency of 17% (EIA 2009). Using data provided by the City of Raleigh, parking lots are estimated to have covered 28.2 million m^2 in 2006. Therefore, assuming that this data is accurate and still applicable, if an area equal to that occupied by parking lot aisles, entrances, exits, and parking spaces were covered with unshaded single-crystal photovoltaic modules, between 19.1 million and 28.8 million kilowatt hours could be generated on an average day. This is equal to the amount of electricity produced daily by an 800 to 1,200 megawatt power plant, assuming that this energy could be stored during peak generation times for use throughout the day (for instance, in charging batteries for electric cars). At an average value of 8 cents per kilowatt hour, this amounts to between $1.6 million and $2.4 million per day. This rough estimate is intended only for the purpose of comparison. The true potential of this resource is dependent on the size, shape, and efficiency of the systems used; the economic costs to install and maintain these systems; shading from trees and buildings; and many other factors.

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