ABSTRACT

Title of Document: SUSTAINABILITY OF AN URBAN TREE PLANTING GROUP: ASSESSING THE CONDITION AND BENEFITS ASSOCIATED WITH RECENTLY PLANTED TREES IN WASHINGTON, D.C.

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Washington, D.C. has experienced a substantial decline in tree canopy cover during the latter half of the 20th century. Casey Trees, a local non-profit organization, was established with the purpose of stabilizing D.C.'s urban forest. Over 10,000 trees have been planted; however, little is known about the condition or benefits associated with these trees. In order to enhance the sustainability of Casey Trees' planting program, I established baseline rates of condition and mortality and created a set of management recommendations based on numerous pre-planting, environmental and socioeconomic variables. Tree mortality was found to be high, with 24-34% of trees not surviving the first few years of growth. Nursery, planting time, landuse, space type, jurisdiction and numerous socioeconomic variables had a significant effect on tree survival. This study suggests that active programmatic decisions can be made to help reduce new tree mortality and ultimately enhance the long-term production of urban tree-based benefits.

Sustainability of an Urban Tree Planting Group: Assessing the Condition and Benefits Associated with Recently Planted Trees in Washington, D.C.

By

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CHAPTER 1: INTRODUCTION

Introduction

Today almost 80% of the United States (U.S.) population lives in urban areas, an increase of 70% since the early 1800's (EPA 2009, Nowak et al. 2010). This rapid expansion has led to a serious and concentrated decline of trees in many U.S. cities (American Forests 2011). The realization and call to action to save and reestablish urban forests is relatively recent and can be largely attributed to the advances in urban forestry tools, techniques and modeling capabilities (e.g., GIS and UFORE i-Tree software). Through the quantification of ecological services, these tools have begun to focus attention on the many benefits trees provide outside the realm of pure aesthetics. At the same time, their ability to more accurately assess changes in canopy cover has highlighted declines and the need for management of urban trees and the many benefits they provide.

Due to numerous challenges associated with harsh urban environments, managing trees can be exceedingly difficult. This is especially true of newly planted trees, which have been shown to incur higher rates of mortality when compared to those that are established (Roman 2006). In order to preserve the many benefits associated with urban trees, considerable research is still needed to curtail the high rates and complicated factors associated with new tree mortality.

Benefits of Urban Trees

In 2002 it was estimated that over 3.8 billion trees comprised the U.S. urban forests, a compensatory or structural value of $2.4 trillion or an average of $630 per tree (Dwyer et al. 2000; Nowak et al. 2001, Nowak et al. 2002). Although these numbers highlight the immense value associated with these forests, they fail to capture the wide array of ecological, social and economic services trees provide in U.S. cities. The creation of new tools, such as the UFORE model and other i-Tree software programs, have helped to quantify these benefits. However, a number of services associated with urban trees are difficult to assess quantitatively (e.g., community and personal well-being). These factors are often linked to the increased presence of urban trees and despite the difficulty associated with quantification, they are essential to the functioning and health of our urban communities.

Ecological Services of Urban Forests

Carbon Storage and Sequestration

Anthropogenic energy use is one of the main contributors to increases in atmospheric gases such as CO_2 (Akbari 2002). Carbon dioxide is an important primary greenhouse gas and has been linked to an increase in earth's average temperature in numerous global climate models (Akbari 2002). Currently, levels of CO_2 are around 390 ppm, which represents an increase of 25% since the preindustrial era (Tans 2011, Global Climate Project 2011, Jo 2005). In 2010, CO_2 levels rose by more than 5%, which is unprecedented in the last two decades (Olivier et al. 2011).

Trees can reduce CO_2 by directly sequestering and storing carbon in their tissues, through the process of photosynthesis. In addition, carbon can be reduced indirectly through proper tree placement that promotes energy use efficiency in buildings and ultimately decreased CO_2 production from fossil fuel based power plants (Nowak 1993). Urban trees store approximately 770 million tons of carbon in the U.S. (Nowak and Crane 2002, Nowak 1993). Carbon storage has also been measured in a number of U.S. cities, including Washington D.C. (D.C.). In D.C. alone, trees have been estimated to store 526,000 tons of carbon, which equates to around a $9.7 million value (Nowak 2006b). Assuming a similar amount of land area, differences found between cities have been linked to both size and density of trees. In general, a city with a higher tree density and larger composition of older trees (with larger diameter trunks) will tend to store more carbon when compared to a city that is similar in size. The dynamic between cities will fluctuate as younger trees mature and older trees begin to decline.

In contrast to carbon storage, younger trees tend to sequester more carbon (Nowak and Crane 2001). As a tree grows and the ratio of photosynthetic processes to respiration decreases, rates of carbon sequestration begin to gradually decline. Overall rates in an area may become negative if more carbon is being released from dying trees than taken up by those that are alive and growing (Nowak and Crane 2001). In D.C. gross carbon sequestration was estimated at around 16,200 tons of CO_2 per year, with an associated value of $299,000 (Nowak et al. 2006b). As with carbon storage, amounts of annual CO_2 sequestration have be estimated in numerous cities across the U.S. including, New York City, Atlanta, Sacramento, Chicago, Baltimore, Philadelphia, Boston, Syracuse, Oakland and Jersey City (Nowak and Crane 2001).

In cities, landuse division is an important consideration, as it can greatly affect the total amount of carbon stored and sequestered, by altering the possible number, growth rate and size of trees (McPherson 1998). Species-specific differences should also be noted, as size at maturity, life span and growth rate all play a significant role in the amount of carbon that can be stored and sequestered (Nowak et al. 2002).

Air Pollution

In addition to CO_2, industrial processes associated with human development release large quantities of harmful pollutants (e.g., O_3, PM-10, NO_2, SO_2 and CO) into the atmosphere. Trees can improve air quality in cities in two primary ways. First, they absorb and internalize gaseous pollutants through stomatal pores in leaf surfaces. Second, they reduce pollution by intercepting and storing airborne particles on plant surfaces. However, this form of pollution abatement tends to be more temporary due to the fact that particles are easily released by rainwater or when leaves fall to the ground (Nowak et al. 2006a). A recent study found that trees in urban cities across the U.S. remove an estimated 711,000 metric tons of pollutants from the atmosphere, which equates to a 3.8 billon dollar value in pollution removal externality costs (Nowak et al. 2006a). Numerous U.S. cities and municipalities, including D.C. have employed the UFORE model in calculating air pollution removal by urban trees (Nowak et al. 2010). In total, D.C.'s urban forest was estimated to remove 540 tons of air pollutants per year, with a $2.5 million dollar compensatory value (Nowak et al. 2006b). Similar studies are being conducted in cities throughout the world. In Beijing, listed by the World Bank as one of the top 10 ten most polluted cities, urban trees are being seriously explored as a tool to help mitigate air pollution (World Bank 2000, Yang et al. 2005). Yang and researchers found that one of the major problems with Beijing urban forest was the high number of small trees, which failed to remove a significant amount of pollution from the atmosphere. Researchers stressed the importance of incorporating and retaining larger existing vegetation in new development projects (Yang et al. 2005).

Improvements in urban forest management may lead to more efficient pollution removal by trees. These include moderate pruning which allows for larger canopies and more efficient pollution removal, selection of species that remove and store pollution at a higher rate and are less susceptible to pollution stress and selection of species that produce less volatile organic compounds (VOCs), since VOCs may react with nitrogen oxides (NO_x) to form O_3 (Benjamin and Winer 1998, Beckett et al. 2000, Nowak et al. 2002, Yang and McBride 2003).

Stormwater Management

Urbanization and the concurrent increase in impervious surface have reduced the potential of urban ecosystems to absorb and retain water. Runoff has become a major problem in many urban areas, where it can lead to “flashy” storm events, problematic flooding and the transport of toxic chemicals and pollutants. These effects not only decrease the overall health of urban ecosystems, they can also lead to costly post-storm recovery and cleanup efforts.

Trees and other vegetation can be used as a cost effective and preventative means to control excess stormwater. Trees can affect stormwater in two primary ways. First, tree branches and leaves intercept and dramatically slow the rate of water flow during a storm event. Second, trees absorb and store water through their rooting and vascular systems (Day and Dickinson 2008). A recent study by Asadian and Weiler looked at rainfall interception loss in an urban area and found that for the two species studied, Douglas fir (*Pseudotsuga menziesii*) and western red cedar (*Thuja plicata*), the interception rate was around 49.1% and 60.9%, respectively. These rates indicate that trees can play a substantial role in managing and slowing water flow in urban ecosystems (Asadian and Weiler 2009). A similar study was undertaken in 2000 looking at the interception losses of ‘bradford’ pear (*Pyrus calleryana*) and cork oak (*Quercus suber*) in an urban environment. Researchers found that interception loss accounted for approximately 15% of the gross precipitation for the ‘bradford’ pear and 27% for the cork oak (Xiao et al. 2000). The variability between the two studies found in regards to interception loss might be explained by differences between species, stand structure, health of trees, storm intensity or local conditions (Xiao et al. 2000). Currently, most studies have focused on stands in natural forests, which may have substantial different outcomes when conducted in urban environments (Anderson and Pratt

1986, Ford and Deans 1978, Johnson 1990, Pook et al. 1991, Prebble and Stirk 1980). Further research on the use of trees to improve urban stormwater management is needed.

Other larger-scale urban studies have used simulation or sample and extrapolation based methods to measure the effect of trees on stormwater runoff (Lamar 1988, Sanders 1986 and American Forests 1996). A simulation study conducted in Dayton, Ohio looked at differing outcomes of storm events based on varying levels of vegetative cover (Sanders 1986). This study found that for a 6 hour, 1 year storm, tree covers of 22% and 50% decreased runoff by 7% and 12%, respectively.

As urban forest management becomes increasingly critical and funding becomes scarcer, recent studies have begun trying to assign monetary value to the hydrological functioning's of urban forests. As Asadiam and Weiler explain, these studies are often based on the "avoidance costs" or the cost of avoiding the building of alternative systems to control stormwater runoff (Asadiam and Weiler 2009). Employing this method, a study by American Forests estimated that U.S. forests were worth around $400 billion in hydrological benefits (American Forests 1996). In a study that examined five U.S. cities, researchers found that annual stormwater benefits ranged from $37,298- 466,227, with an average benefit of $241,613 (McPherson et al. 2005). While a handful of other studies already exist, similar work is likely to be undertaken as tools become more refined and better equipped at capturing the effect of trees on urban hydrology.

Lastly, urban trees can help improve water quality by filtering and storing toxic pollutants that may be present in the soil. In doing this, trees help to prevent these pollutants from being transferred to other land areas or water bodies. According to the EPA, stormwater from urban areas is the second and third most common source of water pollution in U.S. lakes in rivers, respectively. (EPA 1994). There are a number of methods that exist to remove organic pollutants from soils; however, much more development is needed to effectively remove heavy metals (Jensen et al. 2009). According to Jensen et al. the use of trees as heavy metal phytoremediators can serve as a viable alternative to the soil-damaging removal methods that have been previously employed. The study by Jensen et al. evaluated heavy metal uptake by willow (*Salix viminalis*). Researchers found that on moderately polluted soils (2.5 mg Cd/kg and 400 mg Zn/kg) willow seems to be effective, absorbing 0.13% and 0.29% of the most soluble fractions of annual Cadmium and Zinc concentrations, respectively. As Jensen et al. explain similar papers have also focused on willow due to its favorable phytoremediation properties, including a fast growth rate, deep rooting and ability to tolerate temporary water logging (Greger and Landberg 1999, Meers et al. 2007, Robinson et al. 2000, Tlustos et al. 2007, Utmazian et al. 2007, Wieshammer et al. 2007).

Wildlife Habitat

Wildlife has four basic needs which include food, water, cover and space (Yarrow 2009). Trees in both natural and urban environments fulfill much of these requirements, as they can provide cover from storms and predators, food in the form of nuts and berries and help to filter harmful pollutants from drinking water. Urban areas that contain more vegetative habitat, such as riparian areas, natural open spaces and low density housing have been shown to be the most important habitat for urban wildlife (Livingston et. al. 2003). One key feature of these types of areas is that they tend to contain more native vegetation. Many studies have found that local wildlife tends to thrive in natively vegetated areas because they are adapted to it and can more easily utilize these resources (Johnson 1995, Kennedy and Southwood 1984, Mills et al. 1989). In addition to natively vegetative areas, many studies have stressed the importance of vegetative biodiversity of urban areas. Diversity of plant species and thus vegetative structure provide habitat variability that is necessary for the full range of functions utilized by wildlife species (Hohtola 1978, Luniak 1994).

Urban trees have also been shown to play an indirect role in wildlife health and viability. For example, in a recent study published in the Netherlands, tree barriers were suggested as a remedy to ambient noise. This noise was found to be detrimental to avian fitness due to its masking of predator arrival, alarm or mating calls (Slabbekoorn and Ripmeester 2007). As with this study, most work regarding benefits of trees and urban wildlife have looked specifically at avian or small mammals, which tend to be more intimately involved with urban trees (Campbell 2009, Gavareski 1976, Mills et al. 1989, Dooling and Popper 2007, etc.).

Social Benefits of Urban Forests

Crime and Safety

Urban vegetation has been linked in numerous studies to reduced crime and enhanced feeling of personal safety. Several studies have found that as vegetation increases both violent crimes and minor crimes tend to decrease (Donovan and Prestemon 2010, Kou and Sullivan 2001a, Lorenzo and Wims 2004, Sullivan and Kou 1996). In a recent study, conducted in Portland, Oregon, researches proposed that higher levels of vegetation may deter criminals by signaling that a house is better cared for and thus under more vigilant watch (Donovan and Prestemon 2010). Other studies have found that violent or aggressive tendencies, which may contribute to higher crime rates, also have a negative relationship with increased vegetation (Kou and Sullivan 2001b., Mooney and Nicell 1992, Rice and Remy 1998). Kou and Sullivan 2001b found that individuals living in public urban housing surround by higher amounts of vegetation reported significantly less occurrence of violent or aggressive behavior. In addition they found that feelings of mental fatigue, which tended to accompany aggression, were higher in more barren housing units.

The design and maintenance of vegetation is an important aspect in crime deterrence and perceived feelings of personal safety (Talbot and Kaplan 1984, Muderrisolglu and Demir 2004). Overgrown or unkempt vegetation may shield criminal activity and lead to higher crime rates and decreased feelings of personal safety (Kuo and Sullivan 2001, Donovan and Prestemon 2010). One study found that inner city residents preferred well-maintained vegetation in park-like areas over more natural unkempt areas, with survey participants citing that the less-maintained natural areas looked “weedy, disorderly and dangerous” (Tabot and Kaplan 1984). Many studies have found that in various urban settings, heightened crime and decreased feelings of safety may be a function of decreased visibility caused by understory vegetation (Fisher and Nasar 1995, Kaplan and Talbot 1998, Maas et al. 2009, Michael and Hull 1994, Nasar and Fisher 1993, Schroeder and Anderson 1984, Shaffer and Anderson 1985). Enhancing actual and perceived safety associated with urban trees requires careful management decisions. Research shows that even in urban areas people prefer a high density of trees (Hull and Harvey 1989, Smardon 1988). This preference should be accompanied by well maintained vegetation that promotes long distance visibility (Anderson and Stokes 1989, Kuo and Sullivan 1998).

Health and Wellness

Abraham et al. provide a sound conceptual framework for outlining the benefits that urban trees provide in terms of health and well-being (Abraham et al. 2009). They group studies on trees and greenspace into three different categories or “health dimensions”, including 1) mental well-being 2) physical well-being 3) social well-being. Those grouped in the “mental well being" category are further broken down into three different "health promoting landscape effect" categories. First, a number of studies have shown that exposure to trees and greenspace can help improve attention and reduce mental fatigue (Korpela and Hartig 1996, Korpela et al. 2001, Staats et al. 2003, Staats and Hartig 2004). In addition, the aesthetic aspect of trees has been shown to help lessen negative emotions associated with increased stress levels (Ulrich et al. 1991, Hartig et al. 1996). Finally, trees and greenspace have been shown to improve an individual's ability to express positive emotions, such as joy and satisfaction (Hartig et al. 1999, Kaplan 2001, Korpela et al. 2002).

Urban forests and greenspaces are an important component of physical well-being. A study by Addy et al. found that people's desire to participate in regular exercise activities increased when adequate greenspace was available for use (Addy et al. 2004). Furthermore, as distance from greenspace increased, the likelihood of people using these spaces for exercise tended to decrease. Persons who live further away from green areas have been shown to experience higher rates of obesity ($BMI \geq 30$) (Toftager et al. 2011, Bell et al. 2008). One aspect of physical wellness that was not covered in the Abraham et al. review is ability to recover from physical illness. One study found that hospital patients recovered more quickly if they had a view of nature or greenspace (Ulrich 1984). Numerous other studies also report on the positive effects that trees and greenspace can have on physical health (Maller et al. 2005, Moore 1981, Donovan et al. 2011, etc.).

Abraham et al. describes social-wellbeing as the ability of greenspace to enhance bonding and integration of individuals within a community. In numerous studies, greenspace has been shown to enhance social wellness by promoting "social contacts, exchange, collective work, community building, empowerment, social networking and mutual trust" (Abraham et al. 2009, Amstrong 2000, Layden 2003, Wakefield et al. 2007). In addition, these effects have been shown to help in the social integration of more sensitive populations, such as elderly (Booth et al. 2000, Kweon et al. 1998, Milligan et al. 2004) and minorities (Rishbeth and Finney 2006).

Economic Benefits of Urban Forests

Energy Use Savings

A number of studies have linked the presence of trees to a reduction in energy consumption. A properly placed tree can lower energy use in three primary ways (Akbari 2002). First, through canopy shading a tree can block out excess solar radiation that may lead to an increase in ambient temperature. In certain climates, trees can also work as "shelterbelts" blocking hot winds currents that may increase cooling costs. During winter months trees may act as insulators, blocking out cold air currents that may increase heating bills. Finally, trees can lower energy use through evaporative cooling. On hot days, the release of moisture from vegetation through evaporation can substantially lower air temperatures and directly contribute to lowered energy consumption (Akbari 2002).

It has been reported that electricity demand in cities increases by 2-4% for each 1°C increase in temperature (Akbari et al. 1992, Akbari et al. 2001). Trees have been shown to greatly help mitigate the effects of temperature on energy use. In a study conducted in Florida, researchers measured the cooling energy consumption of a building before and after the planting of trees and shrubs. They found that after vegetation was in place, cooling-electricity savings could be as high as 50% (Parker 1981, Akbari et al. 2001). Furthermore, Akbari and researchers found that for two households, surrounding vegetation reduced seasonal cooling costs by between 26% and 47% (Akbari 1997). Similar findings have been found in large scale simulation studies (Taha et al. 1996, McPherson and Simpson 2003).

Despite these findings, recent research has stressed the need for proper placement of trees and consideration of other factors such as tree maintenance costs. A recently published study suggests that trees planted on the west and south side of a house reduce summer time electricity use, while those planted on the north side of a house actually increase energy use (Donovan and Butry 2009). They explain that on the north side of a house trees fail to cast shadows on buildings that may reduce the effect of hot day time temperatures. Furthermore, they suspect that energy use is actually increased because trees planted close to the house may reduce the cooling effect of wind, slow the release of heat at night or cause more indoor lighting to be used.

In addition to tree placement, another important consideration is the cost of tree maintenance. Depending on location, the combined dollar benefit associated with the effect of trees on reduced energy and air quality costs can be up to $200 per tree. However, maintenance costs have been shown to range from $10 to $500 per tree (Akbari 2002). Thus, to receive the energy benefits that urban trees can provide one must be sure that maintenance costs do not exceed the value of energy reductions (Akbari 2002). These variables along with various other factors such as species, location, climate and building design need to be taken into consideration in energy reduction planning.

Property Values

A recent review of related literature revealed that the majority of published studies display a positive correlation between trees/ greenspace and property value. Furthermore, there were only a few studies that show modest, no effect or a negative price effect of trees on property values (Wolf 2007). These studies employ a variety of techniques to assess the effect of trees on value, including subjective questionnaires and surveys and more objective studies that look at actual market transactions (Wolf 2007). An example of the first method includes Selia and Anderson's survey studies that asked homebuilders in Georgia and Massachusetts to estimate the cost associated with tree removal policies (i.e., cost to clear lot, cost to thin trees and cost to preserve trees). Ultimately, builders estimated that tree preservation tended to cost slightly more than clearing or thinning a lot. Despite this finding builders were always able to recover if not exceed the extra costs associated with preserving trees through an increase in property value associated with lots that contained preserved trees (Selia and Anderson 1984, 1982). Other studies have asked homeowners and real estate appraisers to estimate differences in home values based on a series of visuals that contained differing levels of tree cover. In each of these studies, properties with more tree cover tended to have a higher estimated value (Payne 1973, Payne and Storm 1975, Society of the Advancement of Education 1994).

Other reviewed studies use actual sales data or market transactions to examine "willingness to pay" for a property with enhanced urban forestry characteristics (included enhanced tree density and structure on or near a given property). Dombrow et al. used a multiple regression analysis to explore effect of trees on actual property value, finding that in the given market, mature trees contribute around 2% to the value of a home (Dombrow et al. 2000). Similarly, Anderson and Cordell found a fairly strong positive correlation between the number of trees in a front yard and the selling price, with a 3.5-4.5% increase in sales prices for properties with trees (Anderson and Cordell 1988). Tree cover and greenspace surrounding a property has also been shown to increase property values. Morales et al. found that good tree cover in a neighborhood can increase the price of a property by 6%-9% (Morales et al. 1976). View and nearness to trees and greenspace has also plays a role in increase values, with property prices tending to be higher as distance from greenspace is decreased (Correll et al. 1978, Luttik 2000, Tyrvainen and Miettinen 2000, Crompton 2001, Wachter and Gillen 2006).

Threats to Urban Trees

Despite the many benefits that urban trees provide, ensuring the establishments and longevity of these trees can be challenging. Urban trees are confronted with many of the same challenges that that threaten trees in natural forests including stochastic events such as tornados, wildfires and hurricanes and biotic threats such insects, diseases and invasive plants. These threats are compounded by the effects of a changing climate, which has altered temperatures (often increasing the presence of insects and disease or creating a climate environment that is no longer suitable for tree establishment and survival) and the pattern and intensity of storm events (Nowak et al. 2010). In addition to these threats, urban trees face a set of unique challenges that are shaped by the intimate anthropogenic influence that is distinctive of urban areas. It is these factors that ultimately contribute to the substantially lower survival rate observed in urban trees. Depending on planting location, urban trees have been found to live only around 10-60 years, substantially shorter than trees growing in a natural setting (Foster and Blaine 1978, Moll 1989, Skiera and Moll 1992). The following sections will focus on highlighting the unique urban-based problems that threaten the suitability of city trees.

Space Limitations

Plans for urban development often lack the proper consideration of tree planting needs. Meeting these needs, especially in crowded urban areas is critical to the establishment and longevity of urban trees. One major challenge to urban tree survival is limited space. In a survey based study, soil space limitation was reported as the number one factor effecting tree survival, with other space related problems (e.g., soil compaction and insufficient water) following (Mijin

1992). Similarly, other studies list space related issues in the top three factors effecting tree longevity (Betty and Heckman 1981, Gilbert and Bradshaw 1985). Soil space problems come in two basic forms, which include above and below ground limitations (Majin 1992). Below ground, confining tree boxes or plots can restrict rooting systems and impede a plants' ability to uptake water and nutrients necessary for growth and survival. There is a long history of research highlighting proper planting guidelines, including tree plot spacing techniques and procedures (examples of some recent publications include: Appleton and French 2004, New York City Parks and Recreation 2008, Towbridge and Bassuk 2004, etc.). Despite this large body of literature inadequate spacing considerations continues to be a problem in a number of urban areas. A recent study conducted in Hong Kong found that the city failed to provide sufficient spacing for some 87% of street trees that were assessed (Conservancy Association 2009). In addition to below ground constraints, above ground space is often limited. Overall distance or space from human development can lead to problems such as root compaction, vandalism and mechanical damage. This may again impede a plants' ability to uptake proper amounts of water and nutrients. A literature review on soil compaction provides a number of studies that have shown excessive soil compaction in heavy traffic urban areas and the negative impacts this can have on urban tree survival (Day and Bussuk 1994). One study specific to D.C., looking at soils in the National Mall, found extremely high compaction levels with bulk densities ranging from 1.7 to 2.2 g/cm^3 (Patterson 1977). As Day and Bussuk explain, this level of compaction has been shown to greatly affect root growth and ultimate longevity of urban trees (Chiapperini and Donnelly 1978, Pan and Bassuk 1985, Zisa et al. 1980). In general, bulk densities >1.47 g/cm^3 in clay soils, >1.65 in silty soils g/cm^3 and >1.80 g/cm^3 in sandy soils are highly restrictive to root growth (NRCS 2008).

Space Limitations: Environmental Effects and Physiological Response

The primary environmental problems associated with above and below ground space constraints is limited or excessive soil water. Limited soil water has been cited as a common problem in urban environments, especially with street trees which tend to have smaller tree plots, higher rates of foot traffic and more impervious surfaces (Gerhold et al. 1975, Foster and Blaine 1977, Tattar 1980, Staby 1981, Spirn 1984, Lamaire and Rossisnol 1999, etc.). Small tree plots ultimately limit the lateral extension of roots, preventing the growth of an adequate uptake system. Furthering this problem, compaction by heavy foot traffic and mechanical equipment can make soils less porous, limiting the ability of water to percolate into the root zone and diminish a roots ability to penetrate soil and uptake water and nutrients (Witlow et al. 1992, Day and Bussuk 1994). The lack of water effects trees at a cellular level, causing loss in turgidity and wilting. If a tree reaches its permanent wilting point, normal metabolic functions cease and tree death will likely follow. Temporary water stress, prior to a tree reaching its wilting point, is not lethal; however, it can lead to loss in photosynthetic productivity and ultimately weaken a plants ability to combat other environmental stressors (Majin 1992, Nilsen and Orcutt 1996, Larcher 2001).

Excess soil water can lead to tree “drowning”, which has been shown to be a problem in urban areas, but is typically more disputed then water stress. Majin’s 1992 thesis notes that studies (Kozlowski 1986) have cited water drowning as major cause of tree mortality; However, managers and other urban tree professionals do not consider this factor to be one of their major concerns (Majin 1992). Nevertheless, excess water can be caused by small tree plots that limit the ability of water to effectively drain. Backfill that has low porosity or high clay concentration can slow drainage and further intensify tree drowning (Trowbridge and Bassuk 2004). Poor drainage around a trees' roots can lead to anaerobic conditions that limit the roots ability to uptake oxygen. Oxygen is needed by a plant to perform a number of functions, including movement of nutrients and aiding in support. Furthermore, anaerobic conditions facilitate the buildup of substances (e.g., lactic acid, butyric acid, sulfides, etc.) which may be lethal to tree roots (Nilsen and Orcutt 1996, Larcher 2001).

Increased Pollution: Air and Soil

Pollution concentrations tend to be higher in cities then surrounding rural or suburban areas (Inman and Parker 1978, Lovett et al. 2000, Konijnendijk et al. 2005, Pouyat et al. 2007a,b, Pouyat et al. 2008). These patterns are the result of both concentrated industrial processes and the increased levels of pollution associated with high population densities. The release and transfer of toxins into the air and soil cause both acute and chronic stress that can weaken a trees ability to cope in harsh urban environments.

Air Pollution

Air pollution in urban areas has been linked to a number of sources including the combustion and burning of dirty fossil fuels during industrial processes, the combustion of transportation engine exhaust and the high energy consumption of developing countries, such as the U.S. The production of pollution from these sources includes primary pollutants (sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon dioxide (CO_2), particulate matter (PM)) and secondary pollutants (Ozone (O_3), peroxyacetyl nitrate (PAN)), which unlike primary pollutants are not emitted directly from a source but formed in the atmosphere (Konijnendijk et al. 2005). Numerous studies have looked at the damaging effects that both types of air pollution can have on vegetation (Haagen-Smit et. al 1951, McLaughlin et al. 1982, E.D. Schulze 1989, Mauzerall and Wang 2001, Fuhrer and Booker 2003, etc). Ozone (O_3) is thought to be the most wide spread and damaging plant-toxin in the U.S., causing 90% of air pollution related injuries (Sikora and Chappelka 2004, Brust 2007). This problem and related solutions are complicated, as trees release biogenic volatile organic compounds (VOCs) which react with nitric oxides (NO_x) to contribute to additional ozone formation (Konijnendijk et al. 2005).

Although an extensive body of literature exists on the response of natural vegetation and agricultural species to air pollution, (Haagen-Smit et. al 1951, McLaughlin et al. 1982, E.D. Schulze 1989, Mauzerall and Wang 2001, Fuhrer and Booker 2003, etc.), many recently published studies focusing on urban areas tend to be mostly centered around assessing a trees' ability to remove and store atmospheric pollution (Nowak 1993, Nowak and Crane 2002, Nowak et al. 2006a,b, Nowak et. al 2010).

Soil Pollution

Soil pollutants in urban areas are numerous and derived from a variety of sources. Pollutants included mainly inorganic (e.g., inorganic deicing salt, heavy metals-- Al, As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Zn ect.) and organic elements (e.g., organic deicing salt, pesticides and industrial organics) which are transferred to soil through industrial processes, traffic sources, domestic heating, groundwater, sewage sludge, compost, etc. (Konijnendijk 2005). In general, soil contaminants are higher in city centers and tend to degrade along an urban-rural gradient (Pickett et al. 2011). For example, a study that looked at three highly urbanized areas (i.e., New York City, Baltimore, and Budapest) found that concentrations of lead (Pb), copper (Cu) and nickel (Ni) were 2 -3 times higher than surrounding urban or rural environments (Pouyat et al. 2008). Other studies with similar findings have been reviewed in Pickett et al. 2011 (Fenn and Bytnerowicz, 1993, Bytnerowicz et al., 1999, Pouyat et al., 2007a,b, Carreiro et al., 2009). Although pollution tends to be more concentrated in urban areas, effects have been shown to be highly dependent on factors such as site, species and vegetative life stage (Pickett et al. 2011, Dickinson et al. 2000). In urban areas, roadsides have been shown to receive more contamination and trees in these areas tend to be disproportionally affected (Van Boheman and Janssen van de Laak 2003, Zhang 2006). Willow and oak, which are often used in phytoremediation efforts, have been shown to be tolerant to much higher levels of heavy metal concentrations then other plants (Brown and Wilkins 1985, Denny and Wilkins 1987, Eltrop et al. 1991, Jensen 2009). Furthermore, studies have also found that the overall physiological effect experienced by a plant varies with developmental stage. As one would expect, seedlings have been shown to be less resistant to pollution than saplings or mature trees. They also tend to contain higher heavy metal concentrations than established trees (Lehn and Bopp 1987).

Physiological Response

In general, mortality and physiological response is dependent on toxicity levels (Larcher 2001). If toxicity levels are low, trees may experience very little physiological effect. A high toxicity level may lead to rapid mortality. However, this threshold is highly dependent on a number of factors, including those mentioned above (e.g., site, species and vegetative life stage) (Larcher 2001). In general, pollutants can have detrimental effects on a plants' energy status by disrupting physiological functions such as respiration and photosynthesis (Lacher 2001, Konijnendijk 2005). Pollutants such as deicing salt can burn roots and damage overall functioning of theses tissues, leading to dehydration or the inability of a plant to uptake essential nutrients. Damage from deicing salt is a significant pollution-related problem; however, trees in the north and northeastern U.S. are more heavily affected due to colder conditions and heavier salt applications (Beatty and Heckman 1981).

Increased Air Temperatures

Urban areas have been shown to be around 1 to 10°F degrees warmer than surrounding rural or suburban landscapes (NASA 2002). This phenomenon is often referred to as the "urban heat island" (UHI) effect. The sources of urban heating are numerous, including the presence of heat absorbing buildings and streets, anthropogenic heat sources, aerosol pollutants and the absence of vegetation (Velazquez-Lozada et al. 2006). In a study that compared urban and rural temperatures changes in California, UHI sources alone produced on average a 0.7°F rise in temperature per decade (Akbari et al. 1992). The effects of increasing temperatures in cities are likely to be compounded by "greenhouse" warming, which is expected to increase temperatures by 0.5°F every decade (Akbari et al. 1992). Most studies related to urban vegetation focus on the ability of trees to mitigate increasing urban temperatures (Parker 1981, Taha et al. 1996, Akbari et al. 2001, McPherson and Simpson 2003, etc). There seems to be limited number of studies that review the effects of UHI on vegetation. One study found that downtown sites tended to have higher air temperatures and vapor pressure deficits (VPDs) then surrounding less-urban sites. Researches felt that these differences may have lead to higher levels of damage by lilac borers (Podosesia syringae (Harris) (Sesiidae)) that were observed in the more urban sites (Cregg and Dix 2001).

Increased Air Temperature: Physiological Response

Slight increases in temperature are not typically associated with direct tree loss (Roberts 1977, Larcher 2001). Physiological changes may occur; however, tree loss is more likely to be associated with the compounded effects of temperature with other limiting factors (such as water or nutrient stress). When compounded with other factors, temperature may further weaken a plants susceptibility to secondary problems such as insect invasion, inadequate soil moisture or ozone pollution damage (Cregg and Dix 2001, Pickett et al. 2011). Ultimately, young trees or those that are less adapted to warm temperatures may experience higher stress and associated mortality (Roberts 1977).

Community Involvement

Community involvement, or the lack of, can either benefit or greatly threaten the success of an urban tree. If a community is involved in tree care, they may be able to supplement needs that are not being met by the current environment, helping to correct or lessen the effects of the previously discussed threats. For instance, trees in crowded urban areas often experience space constrains and high amounts of impervious surface that contribute to a lack of usable water. Water availability during the first years of growth is critical to successful establishment (Lilly 2011). Supplemental watering by community members may be able to combat harsh growing conditions. One study that highlights this point well looked at a community tree planting program in Oakland, California. Tree establishment success was measured before and after the programs' enactment. Researchers found that before the start of the program less than 1% of planted trees survived, which sharply contrasted with the 60-70% survival rate that was found after community residents were enlisted to take part in the planting process. The major reason noted to contribute to the successful establishment of planted trees was a sense of ownership instilled in community members through their involvement in the program. Ultimately, redefining the lines of ownership contributed to a higher likelihood of care by local residents (Sklar and Ames 1985).

Because social factors have been shown to play such a critical role in the success of urban trees, a few studies have begun to examine the discrepancies that exist between different community groups or socioeconomic areas (Nowak 1990 et al., Nowak et al. 2004). For example, a study in Oakland, CA found that high unemployment levels were strongly correlated with tree mortality (Nowak 1990). These studies are recent and much potential still exists to elaborate on where discrepancies exist and management efforts should be focused.

Urban Forests in the U.S.

Understanding the challenges that affect urban forests are critical, as substantial declines have been cited in cities throughout the U.S. (American Forests 2011). The first report regarding the state of U.S.' urban forest was published in 1986 by the National Urban Forestry Council (NUFC). After assessing urban trees in 20 major U.S. cities, researchers concluded that urban forests were in decline, with 4 trees lost for every 1 planted (American Forests 2011a). In 1991, a follow-up survey by the American Forestry Association (AFA) found that urban tree loss was an ongoing problem, citing average life span of a city tree to be around 13 years (American Forests 2011a). New satellite imagery and GIS capabilities have allowed AFA to publish more detailed reports over the past decade. From 1999 to 2010, AFA has published reports on over 25 U.S. cities and a number of regions and counties throughout the country, including D.C. These studies reported high rates of urban tree decline and the rapidly increasing imperious surfaces (e.g., roads, highways, buildings) (American Forests 2011). Overall, urban areas in the eastern part of the country have experienced higher tree canopy loss then other parts of the U.S. (American Forests 2011a, Nowak 2010). This is a function of both the proportionally higher amount of vegetative cover and the rapidly expansion of urban areas. American Forests estimates that tree cover in urban areas east of the Mississippi has declined by about 30% over the past 20 years, while the urban footprint has increased by about 20% (American Forests 2011a). Washington, D.C. is no exception, having experienced a 16% decline during the latter half of the 20th century (American Forests 2009).

Urban Forest in Washington, D.C.: Past and Present

Washington, D.C.'s urban forest has experienced both highs and lows in terms of tree canopy cover (Choukas-Bradley 2008). In the 1790's President Washington commissioned European engineer, Major Pierre Charles L' Enfant, to create a plan for the city of Washington D.C. L' Enfant's plans for D.C. were inspired by ground-breaking architectural design that had been incorporated in the creation of European cities such as Paris, London and Rome (Choukas-Bradley 2008). Each of these cities planners realized the need and importance of incorporating trees and greenspace in urban design. Similarly, L' Enfant called for stands of trees along streets and near government buildings (Lawrence 2006, Choukaus-Bradley 2008).

Substantial declines of trees occurred during the Jefferson administration, as people were clearing land for construction and the districts poor were harvesting trees to be used as firewood (Choukas-Bradley 2008). Jefferson's work to reestablish lost trees was short lived and following his time in office substantial pollution of Washington, D.C.'s land and waterways again threatened the sustainability of the urban forest. Although interest was growing in protecting and reestablishing the district's lost trees, not much work was accomplished until after the Civil War (Choukau-Bradley 2008).

In 1872, Alexander R. Shepherd, the governor of Washington D.C. at the time began replanting trees throughout the city. In just a few a years he transformed Washington D.C., turning it into a livable, clean and more aesthetically appealing city (Choukas-Bradley 2008). During this time D.C. came to be known around the world as the "City of Trees" due to the number and diversity of trees that had been planted across the district (Choukas-Bradley 2008, Casey Trees 2011).

Despite this resurgence of D.C. urban trees, changes during the 20th century introduced a series of new challenges to D.C.'s urban forest. Large-scale changes such as the automobile and the introduction of exotic pests and pathogens (e.g., Dutch elm disease, dogwood blight) lead to substantial declines of D.C. urban tree canopy cover (Choukas-Bradley 2008). In addition, local changes such an increase in underground gas leaks and the dumping of briny water used in ice cream production may have contributed to additional losses (Choukas-Bradley 2008).

In 1999, American Forest (AF) first mapped tree cover losses that occurred in Washington, D.C. during the latter portion of the 20th century. They found that urban tree cover declined from 37% in 1973 to 21% in 1997 (American Forests 1999). This substantial lost of tree cover in the nation's capital has resulted in a series of events compelling the preservation of D.C.'s urban forest. Local and regional initiatives have called for an Urban Tree Canopy Cover (UTC) goal of 40% in over the next 25 years. Currently, tree cover in the D.C. area is around 30-35% percent (Nowak et al. 2006b, O'Neil-Dunne 2009). In order to meet the UTC goal, it is estimated that D.C. will need to gain approximately 2,041 acres (rate of 100 trees per acre) of urban canopy cover over the next 25 years, which equates to the planting and establishment of 216,300 trees by 2035 (Casey Trees 2011).

Casey Trees

Casey Trees, a local non-profit organization, was created as a direct response to the reported decrease in D.C.'s urban tree canopy. It was officially established in 2002 through a joint partnership between concerned citizen Betty Brown Casey and the Garden Club of America (Casey Trees 2011). Its sole purpose has been to support local government in protecting, enhancing and restoring D.C.'s urban forest. Since 2003, this organization has planted more than 10,000 trees across D.C., at a rate of about 900 trees per year. Trees are planted through a set of different programs, including the Community Tree Planting Program (CTP), American Elm Restoration Program and The Tree Rebate Program. The CTP program, plants groups of trees on both private and public property upon request of individuals, community organizations or local government. Individuals requesting trees through this program must meet a series of requirements before planting begins. Initially, programs participants are required to fill out an application form (Appendix 1). Selected trees must comply with a list of pre-selected species that have been shown to thrive in both urban areas, as well as within the D.C. climatic zone (Appendix 2). In addition, participants must agree to a set of maintenance requirements that includes weekly watering of trees. After an application is reviewed and selected by staff and the organization's "Citizen Forests", appropriate location and species selection are discussed with the participant(s). Citizen Forests, volunteers trained by Casey Trees staff on proper planting techniques, lead a crew of volunteers in planting the selected trees in the pre-determined locations.

The second largest program, the American Elm Restoration Program, was the first planting program to be enacted in 2003. The purpose of this program is to replant street tree Elms that had been lost in large numbers to Dutch elms disease (DED) during the 20^{th} century (U.S. Forest Service 2011). Elms were once the main street tree in the U.S., serving both important historical and functional roles (i.e., shade, environmental tolerance) (Kuser 2000). Casey Trees has planted close to 2,000 Elms since the programs enactment, which includes only disease-tolerant cultivars such as Jefferson, New Harmony, Princeton and Valley Forge. Planting location designation and maintenance duties have been assumed by D.C.'s Urban Forestry Administration (UFA), which is under the jurisdiction of the District's Department of Transportation (DDOT).

Finally, the Tree Rebate program is funded through a grant from the Districts Department of the Environment (DDOE). Those that participate in this program are allowed to select a non-invasive tree(s) to plant on their property. Upon documentation and proof of purchase, Casey Trees utilizes DDOT funding to provide a $50 rebate per tree.

In order to quantify the success of these programs, Casey Trees introduced plans for a condition study in 2008, with data collection beginning that same summer. In 2009, a benefit analysis was added to the study. Currently, condition and benefit data have been gathered for three years, with plans for ongoing yearly collection.

Goals

The broad goal of this research was to create a set of management recommendations that will enhance the sustainability of tree planting programs and help reduce the loss in tree cover that has occurred in Washington, D.C. and in urban areas throughout the U.S.

The primary research goals of this study were three-fold. The first goal included establishing a baseline rate of tree mortality to serve as a measure in which to base improvement once recommendations are in place. The second goal was to initiate an investigation of the relationships between tree condition data and a set of pre-determined environmental, socioeconomic and pre-planting variables in order to highlight broad patterns and areas that merit further study. Additionally, this research will add to a small but growing body of work that considers the influence of socioeconomic and landuse factors that have been shown to be detrimentally important to the success of urban tree planting, but are currently underrepresented in the literature.

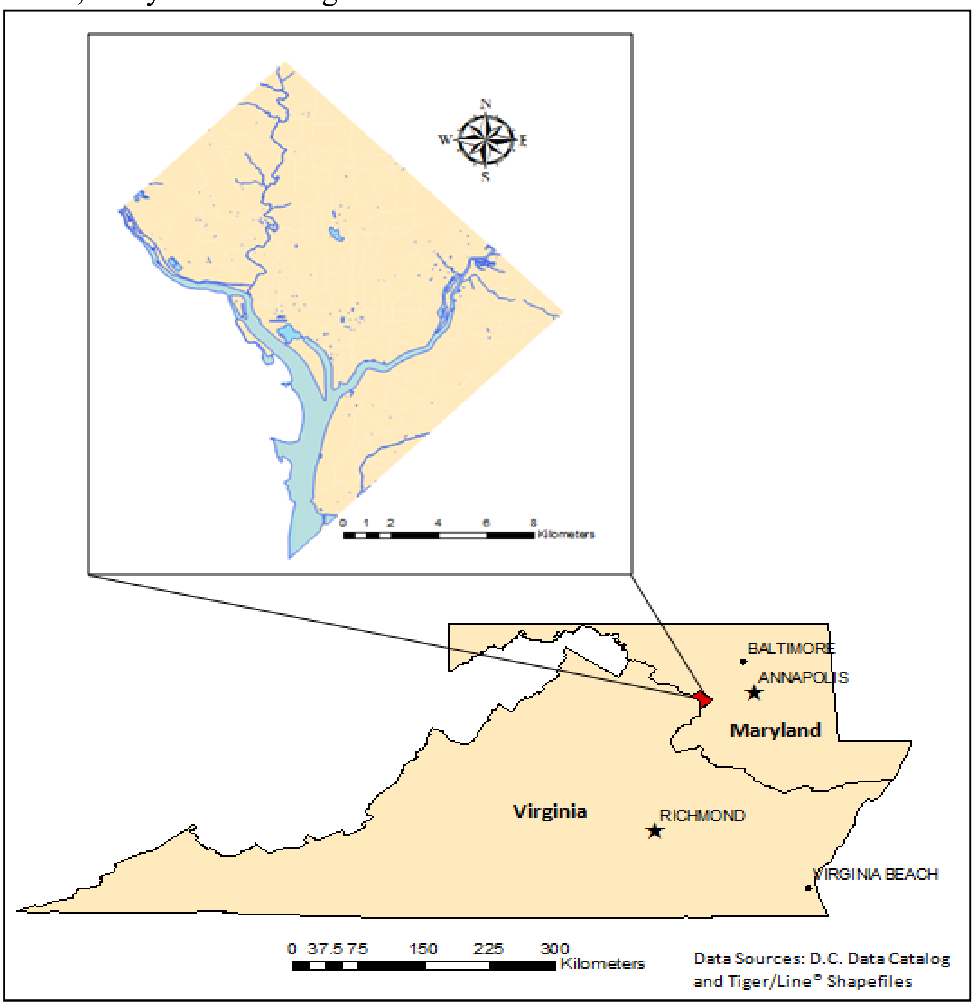
The final goal of this study was to use the Urban Forest Effects Model (UFORE) to assess ecological benefits, including carbon storage and sequestration, pollution abatement and structural value associated with the newly planted trees. These types of analyses can benefit planting programs in various ways. First, calculated benefits can be used as a baseline and a means of extrapolation once new plantings are in place. Finally, this information can be utilized to support educational projects that emphasize the value of urban trees or as a means of garnering additional support for tree planting programs.

CHAPTER 2: MATERIALS AND METHODS

Study Area

Washington, D.C. is located in the mid-Atlantic region of the U.S., surrounded by Maryland on its northwestern to southeastern boundaries and Virginia to the southwest (Figure 2.1). It has a land area of approximately 159 km^2; with the federal government owning 58% (26 km^2) of the land containing the city's urban tree canopy cover (UTC) (O'Neil-Dunne 2009, U.S. Census Bureau 2011). Two major bodies of water, the Potomac and Anacostia Rivers, comprise around 18 km^2 or 11% of D.C.'s total geographic area.

Figure 2.1: Map displaying Washington, D.C.'s location in relation to neighboring states, Maryland and Virginia



Climate and Environment

Washington, D.C. is in plant hardiness zones 7-8, which is indicative of a temperate climate. Winter months are typically mild, with snowfall averaging 43 cm and temperatures around 36°F in the coldest month. Rainfall tends to be highest in May, but is relatively well disturbed throughout the year, with around 56 cm falling annually. Overall weather during spring and fall tends to be quite mild. Summer is typically hot with high humidity, with highs averaging around 80°F. Despite a normally temperate climate, D.C. has experienced record highs in terms of winter snowfall and summer temperatures over the past few years. These extremes are worth mentioning, as they may affect the growth and establishment of newly planted trees (The Weather Channel 2011, NRCS 1975).

Mainly due to climate, D.C. and other urban areas of the northeast, have the potential to support both a large tree species richness and percentage of cover. Canopy cover amounts vary greatly across D.C. Northwest D.C. contains the highest tree canopy cover, with some areas achieving as much as 65% (Figure 2.2). As one would expect, cover amounts tend to be the lowest in the center of the city and increase near the more suburban boundaries.

Figure 2.2: Percent tree cover throughout Washington, D.C. displayed by census tracts

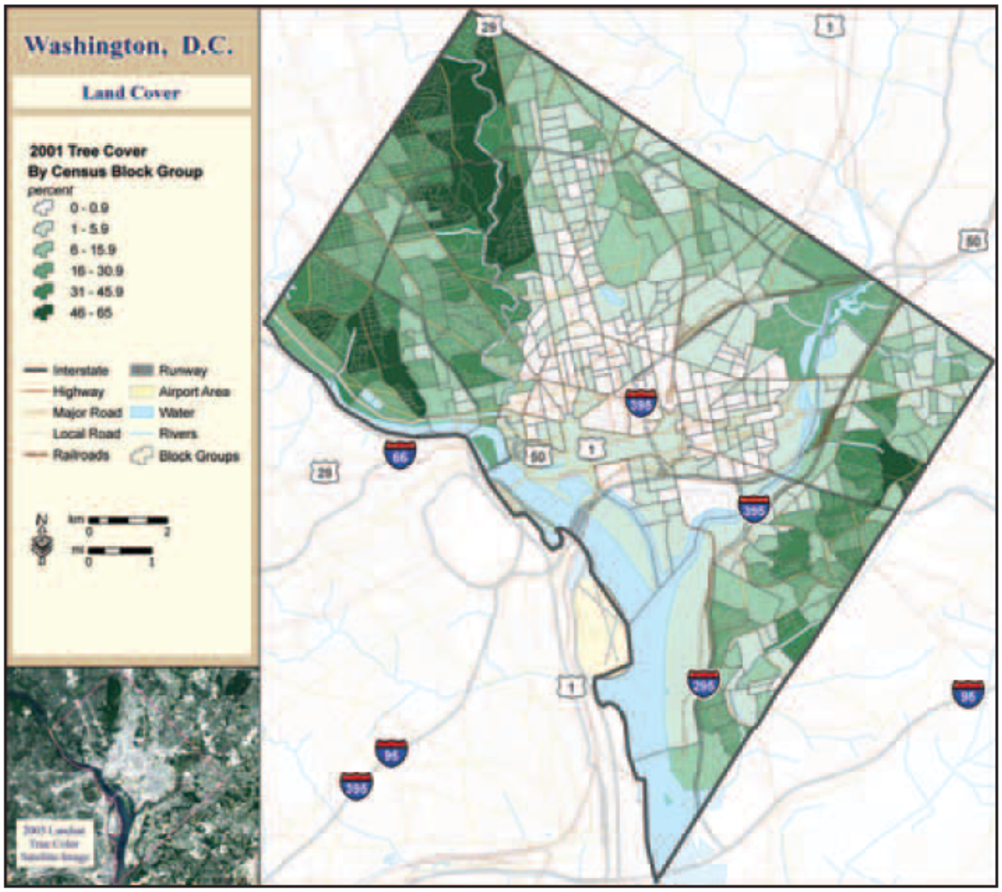


*Figure was obtained from Washington, D.C.'s UFORE analysis (UFORE 2006).

In addition to climate, substantial regional variation in geography and underlying soils has supported the development of unique vegetative communities. The two primary geographic provinces that comprise the D.C. area are the Piedmont and the Coastal Plain (NRCS 1975). The fall line runs through the center of D.C., separating the Piedmont on the west from the Coastal Plain on the east. The Piedmont region consists of hard, well to excessively drained loamy soils, with original vegetation typical of eastern deciduous forests, including species such as chestnut, black oak, white oak, chestnut oak, scarlet oak, mockerynut hickory and pignut hickory. The Coastal Plain consists of more sandy soils that support stands of both hardwoods and softwoods (NRCS 1975). Today, small remnants of undisturbed soil and original vegetation can be found in

Rock Creek, Fort Dupont and Glover-Archbold parks. However, urbanization has destroyed or greatly altered much of the original soils and vegetation (NRCS 1975).

Demographics and Socioeconomics

Washington, D.C. has a population of approximately 601,723 people, with the highest densities being reported in the city's center (33,928 people/ square mile) (U.S. Census Bureau 2011, Zip Atlas 2011). African Americans make up the majority of the population (51%), followed by Caucasians (39%) and Hispanics (9%) (U.S. Census Bureau 2011). Income varies substantially throughout the region, with median annual household income ranging from $8,089-107,917 in the different census tracts (U.S. Census Bureau 2000). Income levels tend to be higher in northwestern D.C. and lower in the southeastern portion of the district. In addition, overall tree cover also tends to follow a similar trend, with higher income areas also tending to have a higher percentage of cover (Figure 2.3a-b) (Nowak et al. 2006b).

Figure 2.3a-b: Pictures displaying differences in tree cover that exist between Washington, D.C.'s neighborhoods

A: Georgetown-- one of Washington, D.C.'s more affluent neighborhoods.

*Picture obtained from an online source.

B: Anacostia-- a poorer neighborhood in Washington, D.C.

Methods

Broad Study Parameters

In accordance with inventory parameters established by Casey Trees, trees associated with each planting year were sampled 3 and 4 years after planting (Table 2.1). Two summer sampling periods allowed for the assessment of annual change in condition, while insuring time and budgetary efficiency. Trees planted in years 2005 and 2006 were assessed by Casey Trees in summers 2008 and 2009.

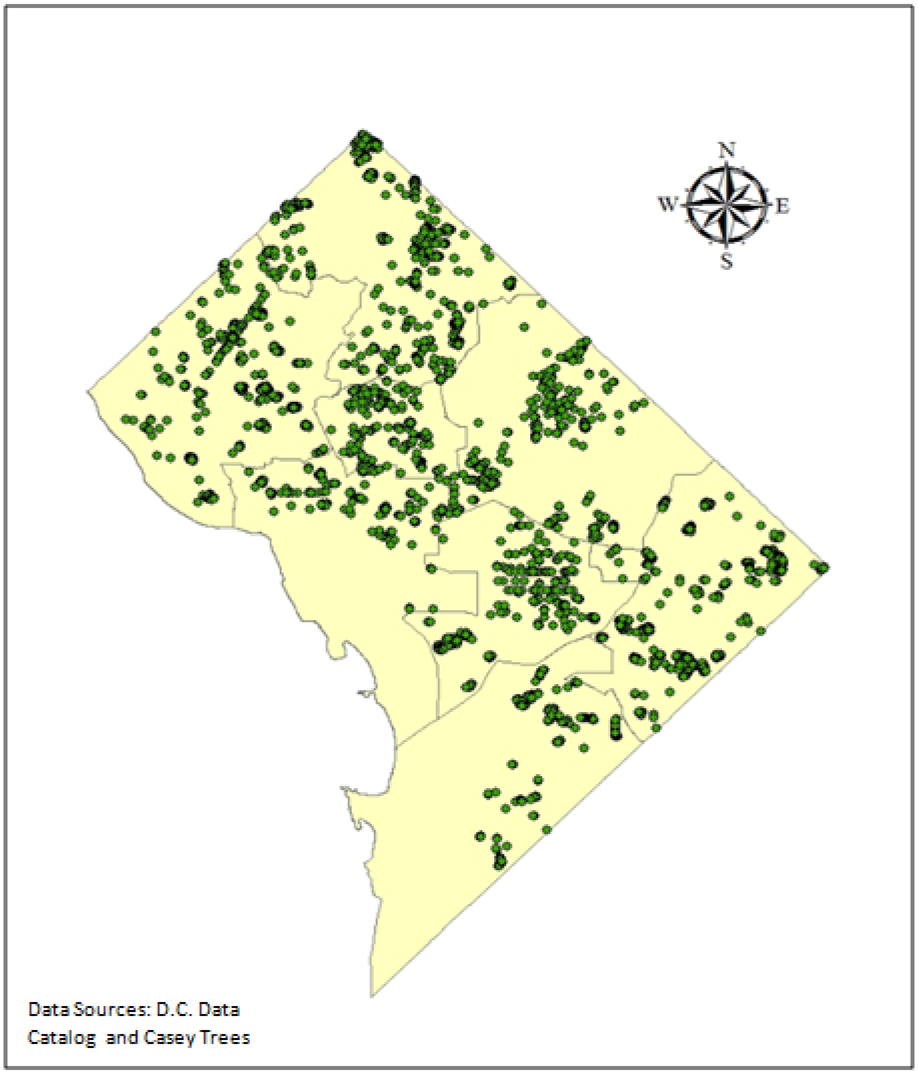
Table 2.1: Data collection parameters established by Casey Trees in 2008 prior to the start of the field study

Planting year(s)	2005	2005, 2006	2006, 2007	2007, 2008
Sampling period	2008	2009	2010	2011
Number of trees sampled	931	1897	1893	2161

*Planting year includes trees planted from January- December

Coordination with Casey Trees for this thesis project began in fall 2010. In addition to an assessment of tree condition, I added a benefits analysis study, using the Urban Forest Effects (UFORE) model to guide field collection and data analysis. Ultimately, this research combines data collected by Casey Trees in summers 2008-2009 with that collected during summers 2010-2011 to assess over 4,000 trees planted throughout Washington, D.C. (Figure 2.4).

Figure 2.4: Trees planted by Casey Trees in years 2005-2008, organized by jurisdictional wards.



Field Techniques

Prior to field collection, tree location coordinates were mapped using a global positional system (GPS). These locations were then plotted on a base map of D.C. using Geographic Information Systems (GIS) software (Figure 2.4). A HP handheld PDA containing the plotted tree maps was used along with paper maps to relocate trees in the field. Once a tree was located, species information contained within the GIS database was used to validate each individual tree. Condition and a series of tree and area based measurements (i.e., diameter at breast height

(DBH), tree height, height to live top, crown width, percent dieback, percent missing, crown light exposure (CLE) and landuse) were recorded in the field. Trees received one of four condition scores (i.e., dead, poor, missing, or good). Dead trees included those that were standing dead, completely lacking the presence of leaves or vegetative matter (Figure 2.5a). Trees that received a score of "poor" included those that had at least 50% of the crown missing and/or contained at least 50% dieback (Figure 2.5b). Missing trees included those that could not be found at the specified site (Figure 2.5c). Typically, there was no way to tell if missing trees had died or were removed. For the purpose of this study and the statistical analysis, missing trees were considered to be functionally dead. In addition, poor and dead trees were combined into one category (i.e., poor+dead) due to the small amount of trees contained within the “poor” condition group. Trees that did not fit these parameters were considered to be in "good" condition (Figure 2.5d).

Figure 2.5a-d: Pictures displaying differences between trees recorded as dead, poor, missing or good in the field, Casey Tree inventory, Washington D.C., summers 2008, 2009, 20010 and 2011.

A: A dead tree observed in the field

B: A tree in poor condition observed in the field

C: Missing trees removed during new construction

D: A tree in good condition observed in the field

After condition was assessed, a number of area and tree based measurements were taken, based on those described in the online Urban Forestry Effects (UFORE) manual (Nowak et al.

2005). The tree diameter at breast height (DBH) was measured at a standard height of 137 cm, using a forestry grade DBH tape. If DBH could not be recorded at 137 cm, the adjusted height was measured and recorded. If multiple stems were present, DBH was recorded for each of these stems. Total tree height was recorded to the nearest centimeter using either a Suunto clinometer or Opti-Logic 800LH laser range finder, depending on availability. If dieback was present at the top of the tree, total height to live top was measured using either the clinometers or range finder. Crown base was measured at the point where the majority of live crown branches began, using a standard forestry tape to measure to the nearest centimeter. If crown base was higher than arm length, the clinometer or range finder was used to assess height. Width of crown was taken for both the N-S and E-W directions, using a compass and a forestry tape held along the axis to measure to the nearest centimeter.

In addition to these structural measurements, percent dieback and crown missing, crown light exposure (CLE) and landuse were estimated for inclusion in the UFORE model. Percent dieback and crown missing were both subjective measures. Dieback missing included a visual estimate of the percentage of vegetative matter that was missing from the top of the tree. Crown missing was the overall percentage of vegetation missing throughout the total crown area. Both of these measures were estimated to the nearest 10% by two individuals in the field. If persons were in disagreement, the estimates were averaged to obtain the final percentage. The CLE was described as the number of sides (N,S,E,W directions and the top) in which a tree received full sunlight. Corresponding CLE scores ranged from 0-5, with a higher score representing more sides receiving full sun. Landuse was assigned from a list of pre-determined categories that included residential, multi-family residential, commercial/industrial, park, cemetery, golf course, agriculture, vacant or institutional.

Statistical Analysis: Pre-Planting and Environmental Variables

A series of pre-planting and environmental variables (i.e., jurisdiction, nursery, stock type, space type, year, season, landuse and genera) were compared to tree condition using a logistic regression analysis. The decision to use logistic regression was based on its unique ability to analyze data sets that contain a categorical (binary or ordinal) dependent variable. After the model was run, factors with a statistically significant (p-value $\geq$0.05) effect on tree condition were assessed using a set of pairwise factor level chi-squared tests. Chi-square analyses are often used to test hypothesis for categorical data. They allow one to compare observed frequencies to calculated theoretical or expected frequencies.

The data for jurisdiction, nursery, stock type, space type, year, season and genera were collected or derived from data obtained by Casey Trees during or prior to planting. Landuse was the only variable that was obtained separately from D.C.'s online data catalog (D.C. 2004) (Figure 2.2).

In this study, jurisdiction was the entity responsible for care of the planted tree. Eight jurisdictional categories were established from the initial data set, including private (PRV), commercial (CMM), National Park Service (NPS), D.C. Parks and Recreation (DPR), D.C. Public Schools (DCPS), D.C. Department of Transportation (DDOT), private schools and universities (SCH), residential (RSD). One hundred fifteen trees that did not fit into a jurisdiction were excluded from the analysis. After the removal of these observations, a total 3,943 trees were statistically assessed (Table 2.2). For jurisdiction and each of the variables described below, an alpha level of 0.05 was used to make the final determination of significance.

Trees were obtained from 15 different nurseries located in the D.C. area. Three nurseries, with small sample sizes of <5 observations within each of the condition cells, were removed prior to the statistical analysis (22 total observations). In addition, observations which were labeled “rebate tree” (nursery unknown) or left blank were removed from the study (204 observations). In total, 3,854 observations were statistically analyzed (Table 2.2).

The nursery stock types included balled and burlapped (B&B) and container grown. In total 4,041 trees were analyzed, with seventeen different or unknown stock types omitted prior to statistical analysis (Table 2.2).

Space types were continuous strip, open land and tree box. Trees in open land spaces were mostly found in small public parks or forested patches within the city. Continuous strip spaces were those that were slightly more confining, with cement and other impervious surfaces surrounding the trees’ roots on two sides. Tree box spaces contained confining pre-formed structures that completely encapsulate a trees’ rooting zone. Trees in continuous strip and tree box space types were mostly street trees. This data set consisted of 4,047 complete observations, with eleven observations removed prior to statistical processing (Table 2.2).

The season and planting year variables were recorded by Casey Trees during the planting process. Four years of plantings were observed (2005-2008). Trees planted in 2008 were only sampled one time during summer of 2011. Until sampling for this planting year is completed in summer 2012, chi-square comparisons are not valid. Planting seasons were as follows; fall (September, October, November), spring (March, April, May), winter (December, January, February) and summer (June, July, August) (American Meteorological Society 1953). After removing 4 missing observations, a total of 4,054 trees were statically analyzed for both the year and season variables (Table 2.2).

Tree species data, collected by Casey Trees, were based on nursery labels. Between years 2005-2008 around 120 different species were planted. In order to obtain larger sample sizes for statistical testing, all years were combined and species were grouped by genera (57 groups). Due to small sample sizes within many of the genera groups, the ten genera with the highest number of tree plantings were isolated to conduct the logistic regression analysis and the factor level chi-square tests. A total of 2,929 trees were statistically assessed (Table 2.2)

Landuse categories were derived from a GIS map obtained from D.C.'s government website (D.C. 2004). Tree planting data points were overlaid on the landuse layer file map using GIS software. After point data and the layer file were combined, a "spatial join" was used to create a new data file in which each tree was assigned to its corresponding landuse. The "spatial join" function is useful with large data sets in which point data (e.g., trees, individuals, etc.) within larger polygons (e.g., landuse, waterbodies, etc.) cannot be visually separated. Trees were divided into seven landuse categories, which included commercial, federal, parks recreation and open space, institutional, local public facilities, mixed landuse and residential lands. Commercial lands comprise the shopping and business corridors of the city. Federal lands are owned and cared for by the federal government, including some of the city's park land. Other parks and open space not cared for by the federal government were included in the "parks, recreation and open land" landuse category. Institutional lands are typically privately owned, including organizations such as universities, museums and churches. Local public landuse areas contain facilities that are critical to the functioning of the city, such as police and fire stations. Mixed landuse are areas in which commercial and residential facilities are combined, typically occurring in the core of a city where apartments tend to be built near or on top of commercial businesses. Residential land was originally grouped into three categories (i.e., low, medium and high density); however, for the purpose of this study, these landuses were combined into a broader residential landuse category. Finally, seven trees missing a landuse data label were omitted before statistical processing (Table 2.2).

Table 2.2: Summary table displaying the pre-planting and environmental factors assessed in the logistic regression analysis and the factor level chi-square tests. The table includes information on each of the factor's levels, data source and the number of observations omitted and assessed prior to statistical analysis.

Factor	Levels	Source	Obs. Omitted	Obs. Assessed
Jurisdiction	Commercial (CMM), National Park Service (NPS), Department of Parks and Recreation (DRP), Department of Transportation (DDOT), D.C. public schools (DCPS), Private (PRV), Residential (RSD), Private schools and universities (SCH)	Casey Trees	115	3,943
Nursery	N1, N2, N3, N4, N5, N6, N7, N8, N9, N10, N11, N12	Casey Trees	204	3,854
Stock type	Balled and burlapped, Container	Casey Trees	17	4,041
Space type	Tree box (TB), Open land (OL), Continuous strip (CS)	Casey Trees	11	4,047
Year	2005, 2006, 2007, 2008	Casey Trees	4	4,054
Season	Fall, Spring, Summer, Winter	Casey Trees	4	4,054
Genera	Nyssa, Quercus, Betula, Magnolia, Acer, Amelanchier, Lagerstroemia, Prunus, Cercis, Ulmus	Casey Trees	N/A (top 10 genera)	2,929
Landuse	Park, recreation and open space (PRO), Residential (RSD), Mixed landuse (MXL), Federal (FDR), Local Public Facilities (LPF) Commercial (CMM), Institutional (INS)	(D.C. 2004)	0	4,058

Statistical Analysis: Socioeconomic Variables

A correlation analysis was used to assess the effect of seven socioeconomic variables on tree condition (dead+poor). The index of variables, based on a similar study in Oakland, California, included population density (persons/sq. mile), median annual family income, median monthly rent, average price of house, percent of individuals under the age of 25, percent unemployment and percent of individuals with a high school diploma or higher (Nowak 1991). Census tract data for each of these variables was obtained from the U.S. Census Bureau's Census 2000 Summary File 3 (SF 3) (U.S. Census Bureau 2000).

A GIS census tract base map was obtained from D.C.'s government website and using GIS software a "spatial join" was used to connect tree data points to individual census tracts. Then socioeconomic data were joined manually to each tract and its corresponding trees. In total, trees were planted in 166 tracts. In order to obtain adequate sample size for a valid measure of condition and mortality data of each socioeconomic variable was broken into larger quantile groups. Average percent dead+poor trees were obtained for each of these quantiles. SAS/STAT® software was then used to estimate and test significance of Pearson's correlation coefficients for percent dead+poor trees and each of the socioeconomic variables. A correlation analysis was also conducted to determine if there was a relationship between each of the socioeconomic variables.

Benefit Analysis: Urban Forest Effects (UFORE) Model

The area and structural tree-based measurements described in the field collection section were entered into the UFORE software program and sent to the USDA Forest Service in Syracuse, NY for processing and calculation of associated tree benefits. Although two summers of data were collected, only one summer of sampling could be included in this thesis due to the long processing period. Ultimately, the benefit analysis assessed 1,391 live trees that were planted between years 2006- 2007.

The three primary benefit components calculated by the UFORE analysis included carbon storage and sequestration, pollution abatement and structural values. Carbon storage is the amount of carbon a tree stores as wood. Trees store more carbon as they grow larger with age (Nowak and Crane 2002). Carbon storage amounts were calculated through the input of measured data into species-specific allometric biomass equations found in the literature (Nowak et al. 2006).

Carbon sequestration is the rate at which carbon is taken up from the atmosphere. It tends to be highest when trees are young and net photosynthetic activity is at optimal level. Annual carbon sequestration rates were found by adding average diameter growth (calculated from genera and diameter class) and tree condition (based on dieback estimates) to the existing tree diameter (Nowak and Crane 2000, Nowak et al. 2006).

Five pollutants considered in regards to air pollution abatement were ozone (O3), nitrogen dioxide (NO2), sulfur dioxide (SO2), carbon monoxide (CO) and particulate matter less than 10 microns (PM10). Hourly pollution removal values were calculated through the use of hybrid multi-layer and big-leaf modeling techniques that employed the use of local weather, air pollution concentration and leaf area data (Nowak 2006).

Finally, structural values were based on the valuation guidelines outlined by the Council of Tree and Landscape Appraisers. These procedures use species, diameter, condition and location information to calculate the compensatory value (i.e., cost of same size tree replacement) associated with a given tree (Nowak 2006).

Prior to the final analysis outliers or extreme values were removed. Outliers had values that returned a z-score of -3 or +3 deviations beyond the mean value. If a genus contained a high number of values outside this range, best judgment was used to determine if a value should remain or be removed from the final analysis.

CHAPTER 3: RESULTS

Composition and Mortality of the Inventory

Tree Composition and DBH

Data were collected for 4,058 trees planted by Casey Trees throughout the D.C. area from 2005-2008 (Table 3.1).

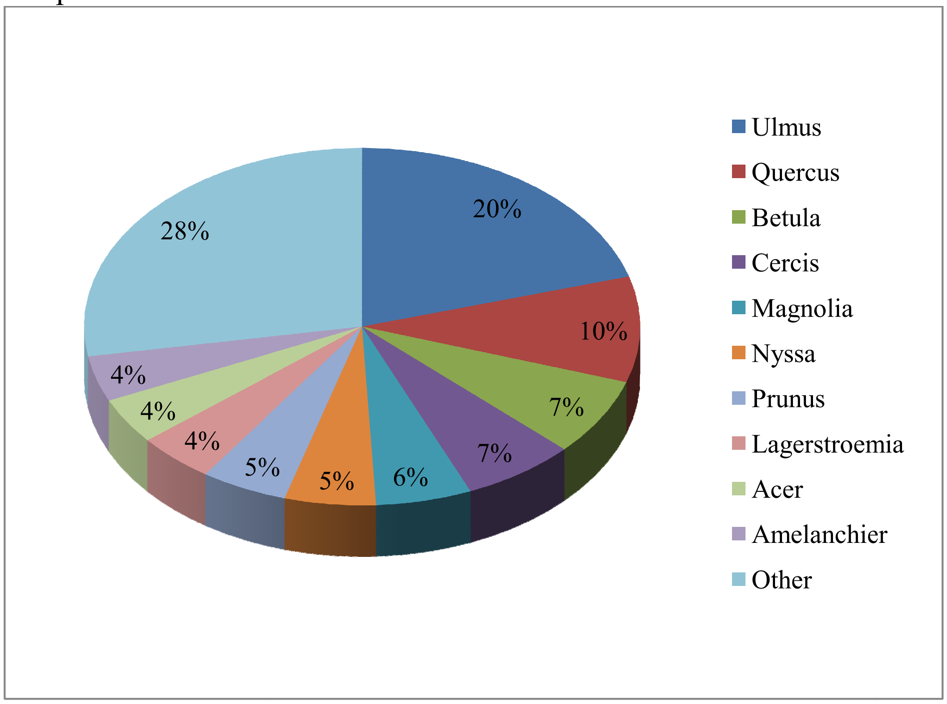
Table 3.1: The number of trees planted each year in Washington, D.C. by Casey Trees

2005	2006	2007	2008
931	966	927	1234

There were a total of 119 different species and 10 hybrid varieties. These species composed 57 genera, with *Quercus* containing the highest species number (12). Other genera with a high number of species included *Prunus*, *Acer* and *Magnolia* which contained 8, 7 and 6 species, respectively.

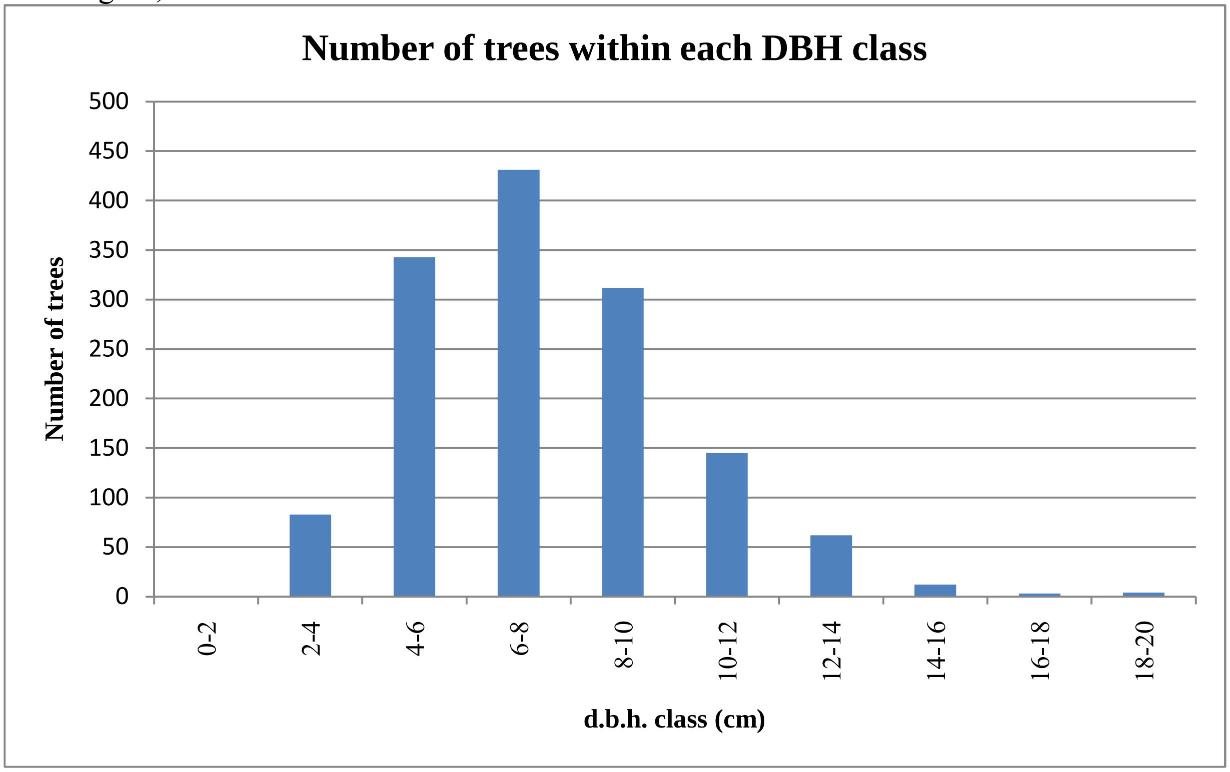
Ulmus contained the highest number of tree plantings, with 824 individuals which represented 20% of the total inventoried trees (Figure 3.1, Appendix 6.5). The American elm species (*Ulmus americana*), planted through the elm restoration program, was the most common tree planted in this inventory. After *Ulmus,* the most commonly planted genera included *Quercus* (10%), *Betula* (7%), *Cercis* (7%), *Magnolia* (6%), *Nyssa* (5%), *Prunu*s (5%), *Lagerstroemia* (4%), *Acer* (4%) and *Amelanchier* (4%) with at least 100 individuals (Figure 3.1). The remaining 47 genera contained substantially less plantings with almost half having fewer than 10 observations.

Figure 3.1: The top ten genera with the highest percentages of plantings, from the Casey Tree inventory, Washington, D.C., observed in summers 2008-2010. The “other” category comprises the remaining 47 genera with almost half containing sample sizes of □10 individuals.



The diameter as breast height (DBH) of trees sampled in summer 2010 ranged from 2-20 cm, with the majority (1,086 individuals or 78% of the live trees inventoried in summer 2010) falling between 2-10 cm (Figure 3.2). Data for summer sampling period 2011 is not yet available.

Figure 3.2: The total number of trees in each DBH class. Trees observed were planted in Washington, D.C. in 2006/2007 and measured in 2010.



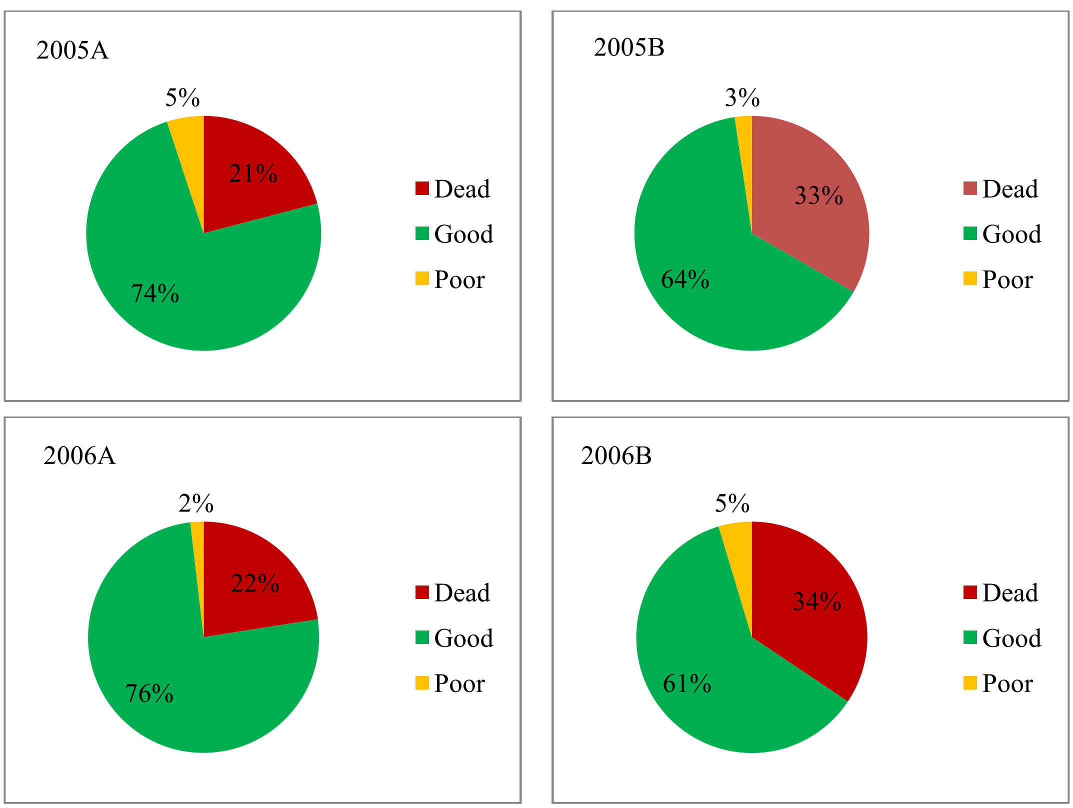
Tree Mortality

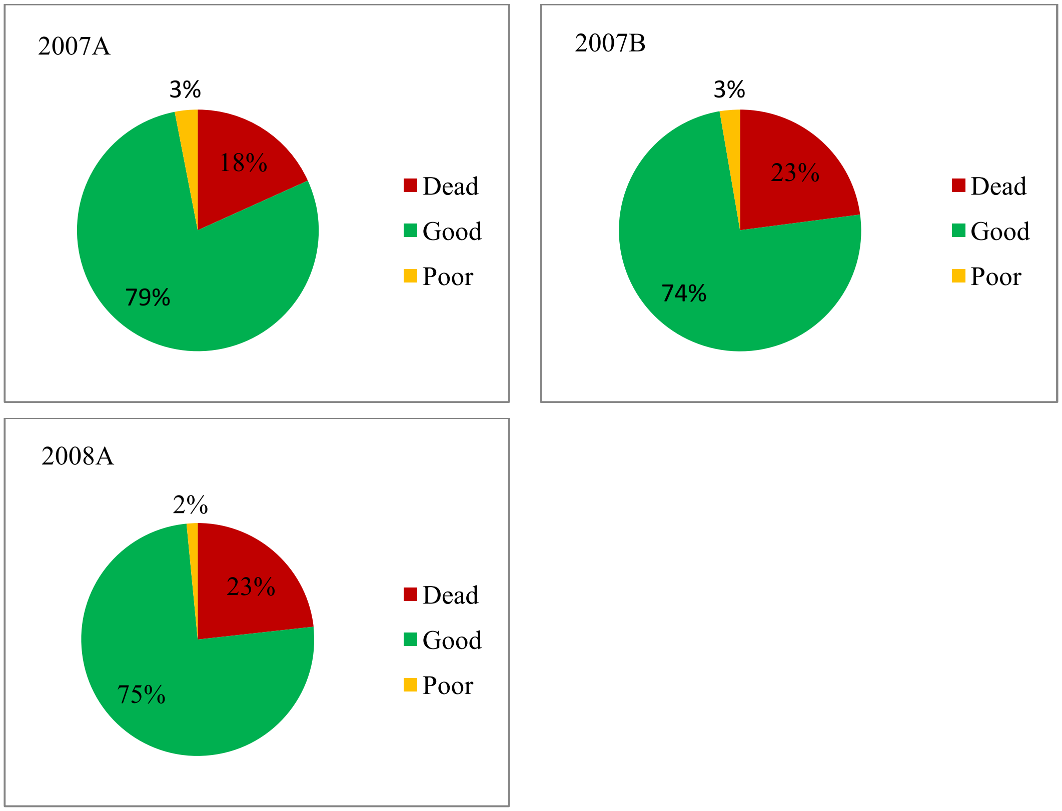
Tree mortality observed during first sampling period (i.e., 3 years post planting) ranged from 18-23%, with an overall average of 21% (Figure 3.3, 2005A, 2006A, 2007A, 2008A). Planting years 2005, 2006 and 2008 had similar rates of mortality, with 21, 22 and 23% dead, respectively. Planting year 2007, with only 18% dead, had a lower mortality rate when compared to each of the other planting years.

When assessing the difference between the first and second sampling periods, mortality increased by 12% for both planting years 2005 and 2006. Planting year 2007 had a substantially lower rate of increase, with only a 5% difference between the two sampling periods. Due to the lack of a second sampling period, change in percent dead could not be determined for planting year 2008.

Tree mortality observed during the second sampling period (i.e., 4 years post planting), for planting years 2005/2006/2007, ranged from 23%-34%, with an overall average of 30% (Figure 3.3, 2005B, 2006B, 2007B). Due to a lower percentage of dead trees observed during the first sampling period and a lower percent increase between the sampling periods, planting year 2007 had a significantly lower percentage of dead trees (23%), when compared to planting years 2005 and 2006 (33% and 34%, respectively).

Figure 3.3: Percentage of trees from the Casey Tree Inventory, Washington, D.C., in the "dead", "good" and "poor" condition categories shown by plantings years 2005, 2006, 2007 and 2008. Lettering after the planting year is indicative of sampling period. Charts receiving an (A) were sampled 3 years after planting (B) were sampled 4 years after planting.





Effects of Pre-Planting and Environmental Variables on Tree Mortality and Condition

The logistic regression model, used to assess the effect of pre-planting and environmental variables on tree condition, showed that all variables except stock type had a significant effect on tree mortality (Table 3.2). Nursery and genera showed the strongest effect with a p-value of <0.0001 and a Wald Chi-square value 60.4 and 53.3, respectively. The factor level effects of each of these variables will be presented in the following sections.

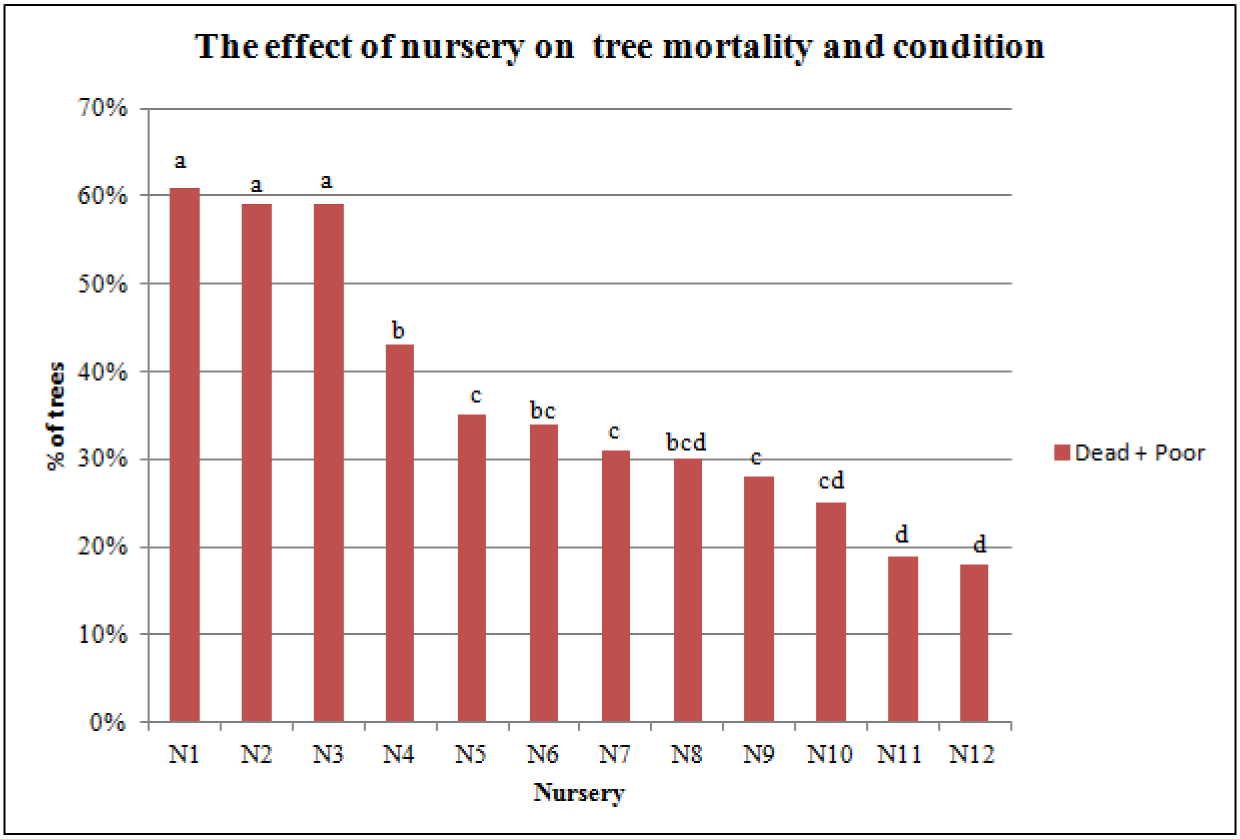
Table 3.2: The results of the logistic regression model used to assess the effects of select pre-planting and environmental variables on trees condition and mortality, of trees from the Casey tree inventory, Washington, D.C., observed in summers 2008, 2009, 2010 and 2011.

Effect	Levels	DF	Wald X^2	p-value
Jurisdiction	Commercial (CMM), National Park Service (NPS), Department of Parks and Recreation (DRP), Department of Transportation (DDOT), D.C. public schools (DCPS), Private (PRV), Residential (RSD), Private schools and universities (SCH)	7	29.1	0.0001
Nursery	N1, N2, N3, N4, N5, N6, N7, N8, N9, N10, N11, N12	11	60.4	<0.0001
Stock type	Balled and burlapped, Container	1	2.5	0.1120
Space type	Tree box (TB), Open land (OL), Continuous strip (CS)	2	6.1	0.0401
Year	2005, 2006, 2007, 2008	3	26.6	<0.0001
Season	Fall, Spring, Summer, Winter	3	40.9	<0.0001
Genera	Nyssa, Quercus, Betula, Magnolia, Acer, Amelanchier, Lagerstroemia, Prunus, Cercis, Ulmus	9	53.3	<0.0001
Landuse	Park, recreation and open space (PRO), Residential (RSD), Mixed landuse (MXL), Federal (FDR), Local Public Facilities (LPF) Commercial (CMM), Institutional (INS)	6	25.3	0.0003

Nursery

The nurseries with the highest number of trees in the dead+poor condition category included N1, N2 and N3 (Figure 3.4, Appendix 7.1). Each of these groups contained at least 100 individual observations. N1 had both the largest sample size of the three (n=277) and the highest percentage of trees in the dead+poor condition category (61%). N2 and N3 contained a similar number of observations (103 and 116, respectively) and percentages of dead+poor (both 59%). At an alpha level of 0.05, there was not a statistical difference between these three nurseries. Nurseries with the lowest percentage of dead+poor included N12 (18%), N11 (19%) and N10 (25%) with again no significant difference between these nurseries. Number of observations varied with N11 having the largest sample size (n=1,221), followed by N12 (n=636) and N10 (n=89). These nurseries were not found to be significantly different from N8 (n=20, 30% dead+poor); however, due to the small number trees obtained from N8, sample size may need to be increased to validate conclusions.

Figure 3.4: The percent of trees from each nursery found to be in dead+poor condition for data collected in Washington, D.C. in summers 2008, 2009, 2010 and 2011. Nursery data was recorded by Casey Trees prior to planting.

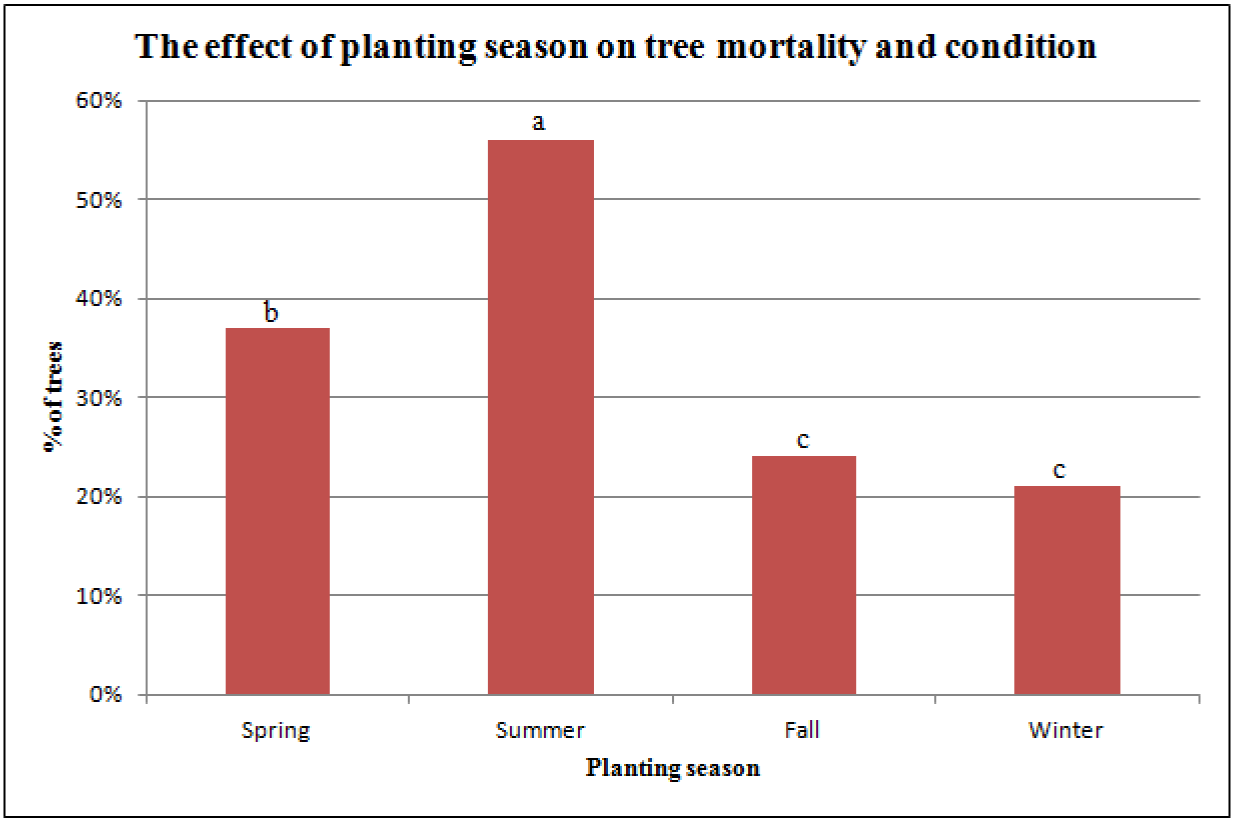


* Different letters above bars indicate significant chi-square differences (p=0.05); N1= 277; N2=103; N3= 116; N4= 423; N5= 387; N6= 159; N7= 220; N8= 20; N9= 203; N10= 89; N11= 1,221; N12= 636

Timing of Planting: Season and Year

Fewer trees were planted in the summer (n=59); however, these trees had a higher percentage (56%) of dead+poor, when compared to each of the other three seasons (Figure 3.5). Those planted in spring, fall and winter all had relatively large sample sizes with ≥489 individuals. The percentage of dead+poor trees found for spring plantings was higher than that observed for summer and winter/fall plantings, which had the lowest percentages of dead+poor (24% and 21%, respectively) with no statistical difference found between the two seasons (p=0.0058) (Figure 3.5, Appendix 7.3).

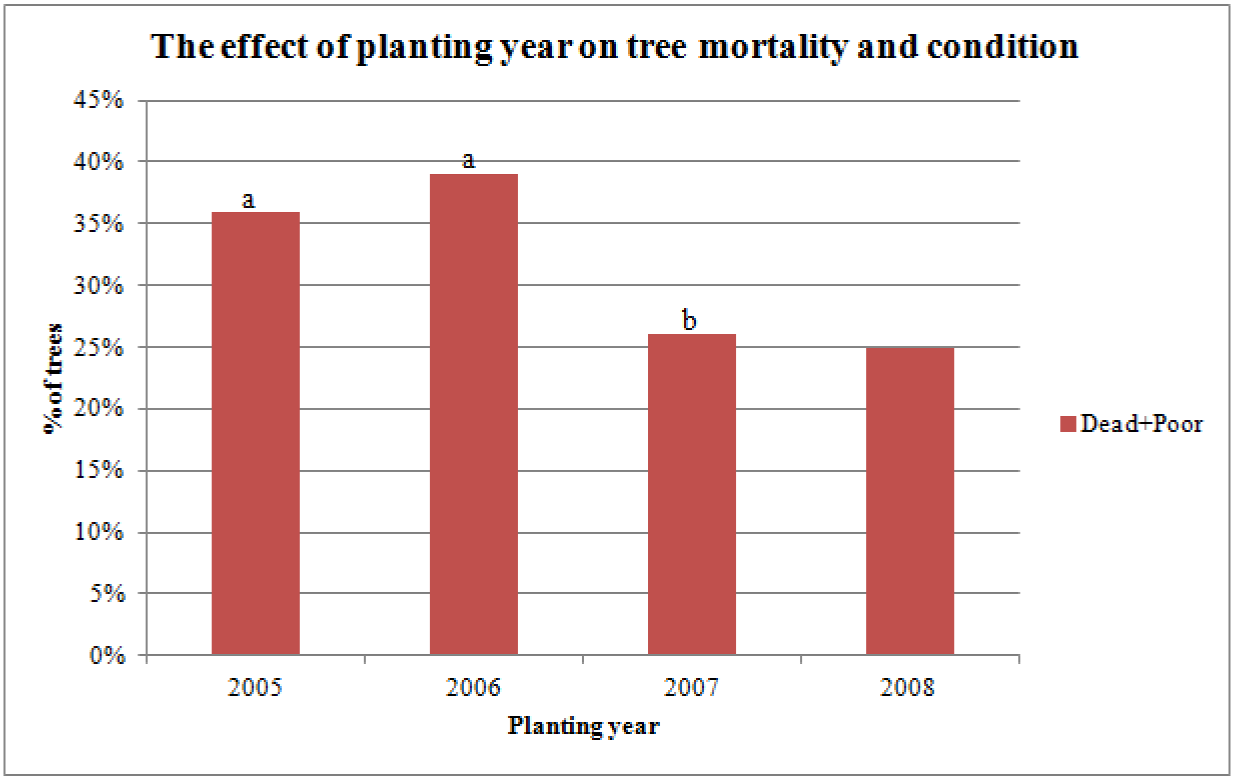
Figure 3.5: The percent of trees from each season found to be in dead+poor condition for data collected in Washington, D.C. in summers 2008, 2009, 2010 and 2011. Seasonal categories were derived from planting date data that was collected by Casey Trees during planting.



*Different letters above the bars indicate significant chi-square differences (p=0.05); Summer= 59; Spring= 2,019; Fall= 1,487; Winter=489

Tree mortality by year was reported in the initial examination of baseline tree condition (Figure 3.3a-d). The yearly findings in the figure below differ slightly from what was found in Figure 3.3a-d due to the addition of poor trees to create the dead+poor condition category that was utilized in the chi-square analyses. As mentioned in the method section, poor trees contained a small number of observations and thus were combined with dead trees to increase the sample sizes before chi-square tests were conducted. Due to their small sample sizes poor trees had very little effect and the results of the chi-square tests were similar to what was shown in figure 3.3a-d. Years 2005 and 2006 were not significantly different (p=0.1422) and both contained a relatively similar number of dead+poor trees (2005=36%, 2006=39%). Year 2007 had a significantly lower number of dead+poor than years 2005 and 2006 (2007=26%). Year 2008 was not included in the chi-square analysis due to the lack of a second sampling period (Figure 3.6, Appendix 7.4).

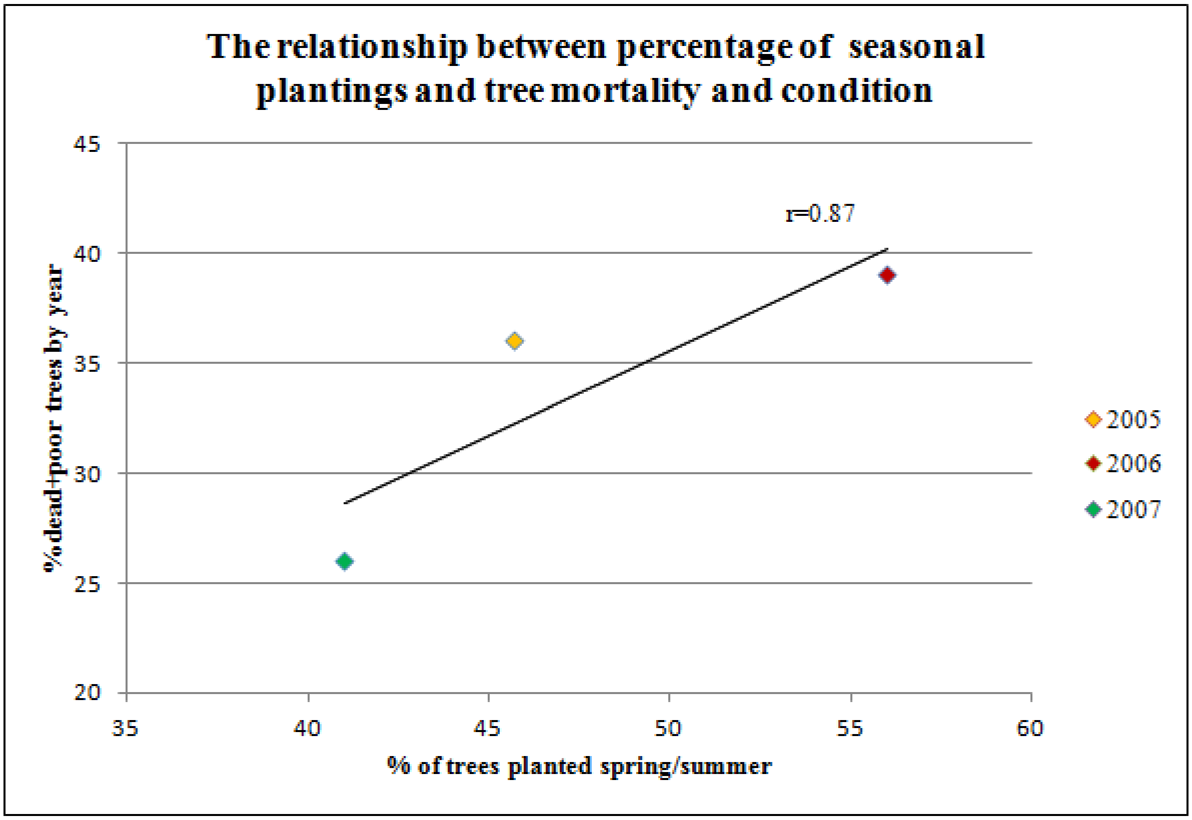
Figure 3.6: The percent of trees from each year found to be in dead+poor condition for data collected in Washington, D.C. in summers 2008, 2009, 2010 and 2011. Planting year was derived from planting date data that was collected by Casey Trees during planting.



*Different letters above the bars indicate significant chi-square differences (p=0.05); 2005= 931; 2006= 966; 2007= 926; 2008= 1,231

If we study the differing amounts of seasonal plantings within each of the planting years, we find that there is a strong linear relationship (r= 0.87) between the percent of dead+poor trees and the percent of trees planted in spring/summer. Year 2008 was not included in the analysis; however, due to the high number of trees planted in spring/summer, the results for this year are likely to be consistent with current findings after the second sampling period is complete (Figure 3.7).

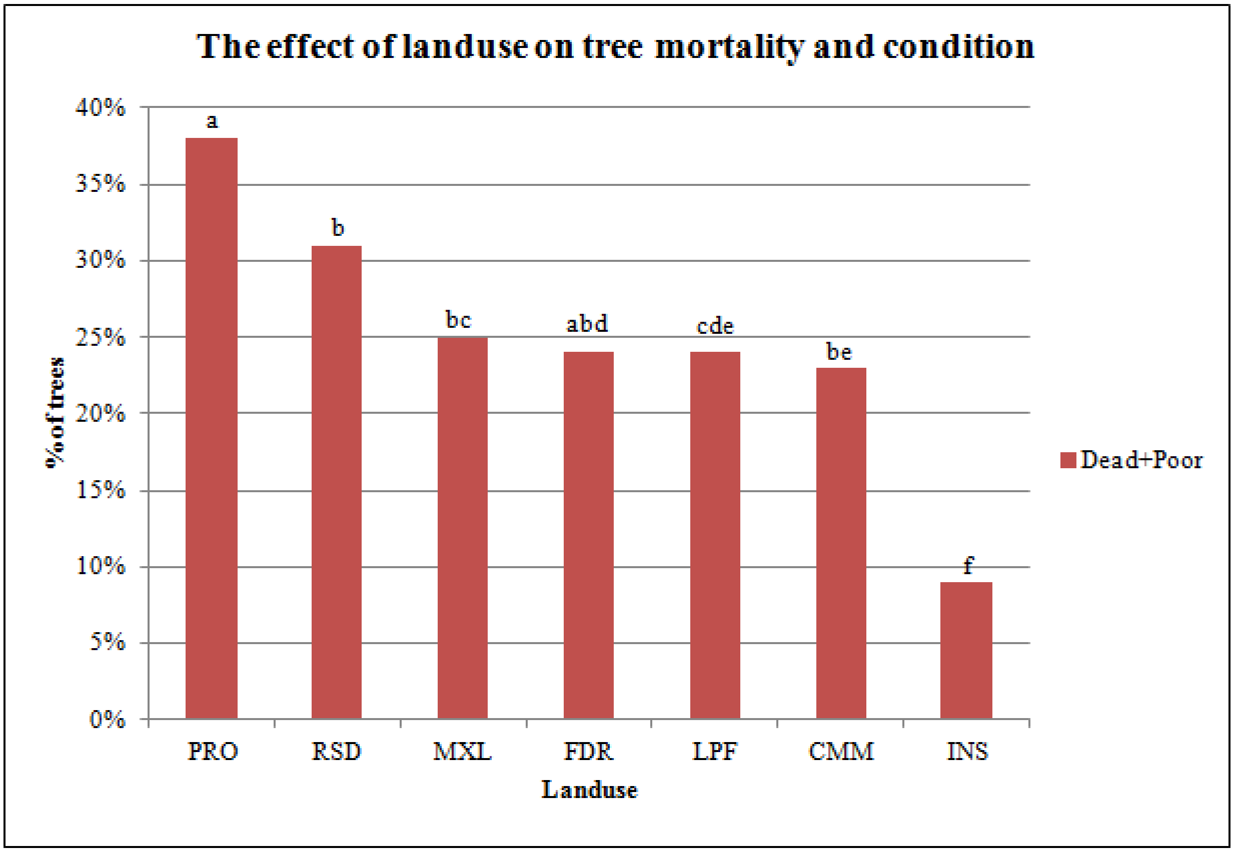
Figure 3.7: The relationship between percent of trees planted in spring and summer months and the percent of poor+dead trees observed in each planting year for trees planted by Casey Trees in Washington, D.C. in years 2005, 2006 and 2007. Planting year 2008 was excluded from this analysis due to the lack of a second sampling period.



Landuse and Space Type

Parks, recreation and open space (PRO) with a sample size of n= 1,095 had a significantly higher percentage of dead+poor trees (38%) than the other five landuse categories (Table 3.2). The only landuse that was found to be not significantly different from PRO was the Federal (FDR) category. However, results may be skewed by the small sample size contained in the FDR group (n=34). The RSD landuse category contained the second highest percentage of dead+poor trees (31%); however, it could not be statistically differentiated from MXL, FDR, LPF or CMM. The statistically similar relationship between MXL, FDR, LPF, CMM is obvious from the graph and the nearly identical percentages of dead+poor trees found within each landuse category (23-25%). The Institutional landuse category, with a sample size of n=164, had a significantly lower percentage of dead+poor (9%) trees than each of the other categories (Figure 3.8, Appendix 7.5, 3.14).

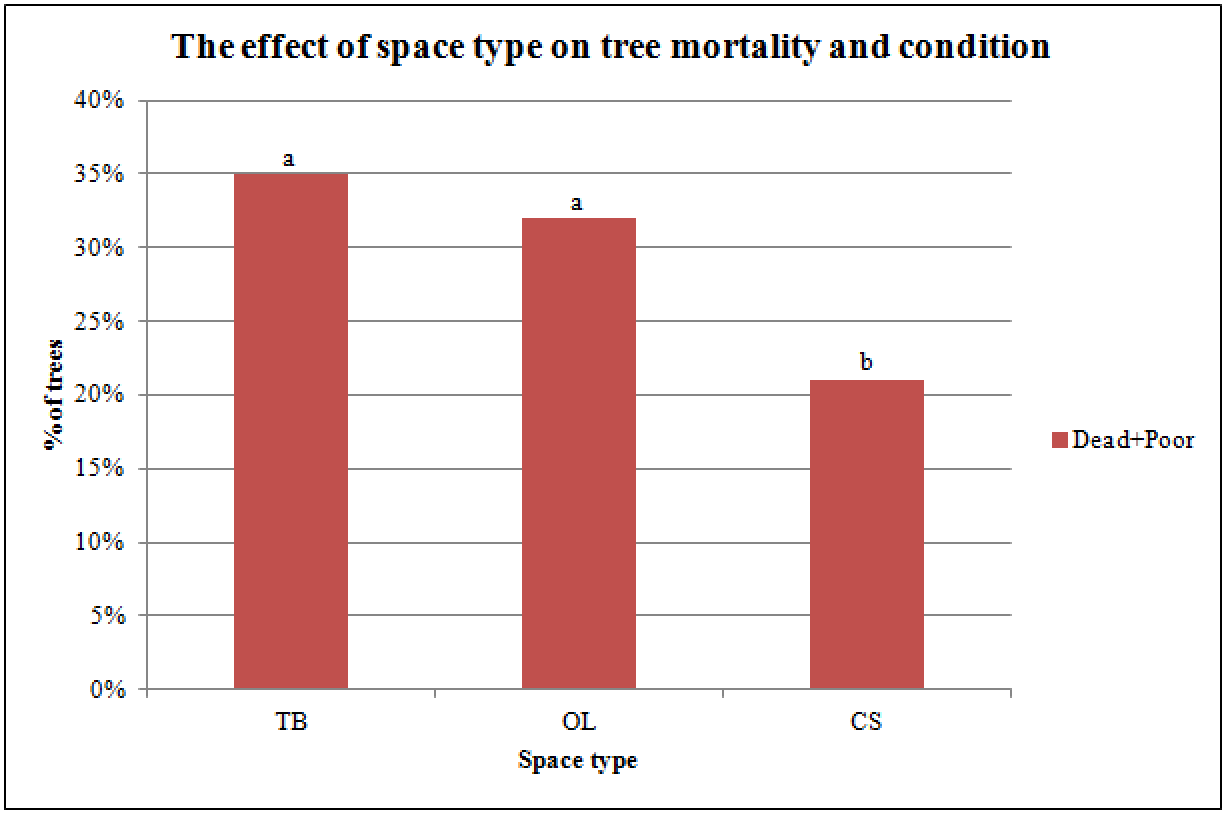
Figure 3.8: The percent of trees in each landuse found to be in dead+poor condition for data collected in Washington, D.C. in summers 2008, 2009, 2010 and 2011. Landuse data was obtained from Washington, D.C.'s online government data catalog.



*Different letters above the bars indicate significant chi-square differences (p=0.05); PRO= Parks, recreation and open space (n=1,095); RSD= Residential (n=2,008); MXL= Mixed landuse (n=151); FDR= Federal (n=34); LPF= Local public facilities (n=34); LPF= Local public facilities (n=430); CMM= Commercial (n=80); INS= Institutional (n=164)

Each of the space type categories had relatively large sample sizes, with the open land (OL) category containing n=2,454, the tree box (TB) category (n=871) and the continuous strip (CS) category (n=722). With similar percentages of dead+poor trees there was no statistical difference between TB (35%) and OL (32%) space types (p-value=0.09). Continuous strip spaces had significantly lower percentages of dead+poor trees (21%) than the other two space types ($p<0.0001$) (Figure 3.9, Appendix 7.6).

Figure 3.9: The percent of trees in each space type found to be in dead+poor condition for data collected in Washington, D.C. in summers 2008, 2009, 2010 and 2011. Space type was recorded by Casey Trees during planting.

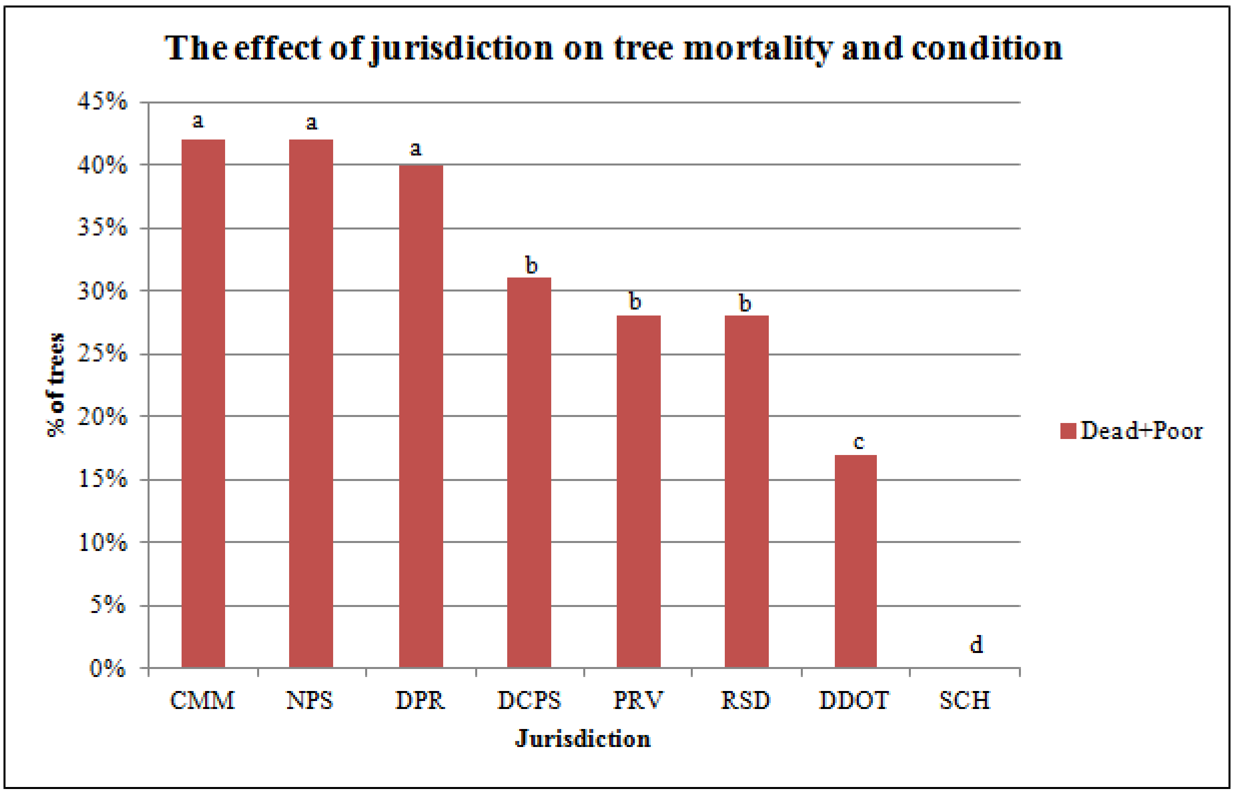


*Different letters above the bars indicate significant chi-square differences (p=0.05). TB= Tree box (n=722); Open land (n=2454); Continuous strip (n=871)

Jurisdiction and Care

In the analysis of jurisdiction and care tree condition fell into four basic significance groups. The first group with the highest percentages of dead+poor trees included commercial (CMM), National Park Service (NPS) and Department of Parks and Recreation (DPR). Each of these groups had nearly identical percentages of dead+poor trees (40-42%) and relatively large sample sizes (n_{DPR}=814, n_{NPS}=351 and n_{CMM}=278). The second group was comprised of D.C.'s Public Schools (DCPS), Private (PRV) and Residential (RSD) jurisdictions, which had intermediate mortality and condition levels, lower than the first group but higher than the third and fourth groups (i.e., DDOT and SCH). Again, each of the jurisdictional categories contained in the second group had a relatively large number of observations (n_{DCPS}=505, n_{prv}=976, n_{rsd}=198). The third group was comprised of D.C.'s Department of Transportation (DDOT), which had a significantly lower percentage of dead+poor trees (17%) then the other six jurisdictional categories, including all other government agencies. The fourth group or schools (SCH) contained the lowest number of dead+poor trees when compared to each of the other jurisdictional categories. This group had the smallest sample size (n=40); however, 100% of the trees were found to be in good condition (Figure 3.10, Appendix 7.7).

Figure 3.10: The percent of trees in each jurisdictional category found to be in dead+poor condition for data collected in Washington, D.C. in summers 2008, 2009, 2010 and 2011. Jurisdictional data was collected by Casey Trees during planting.

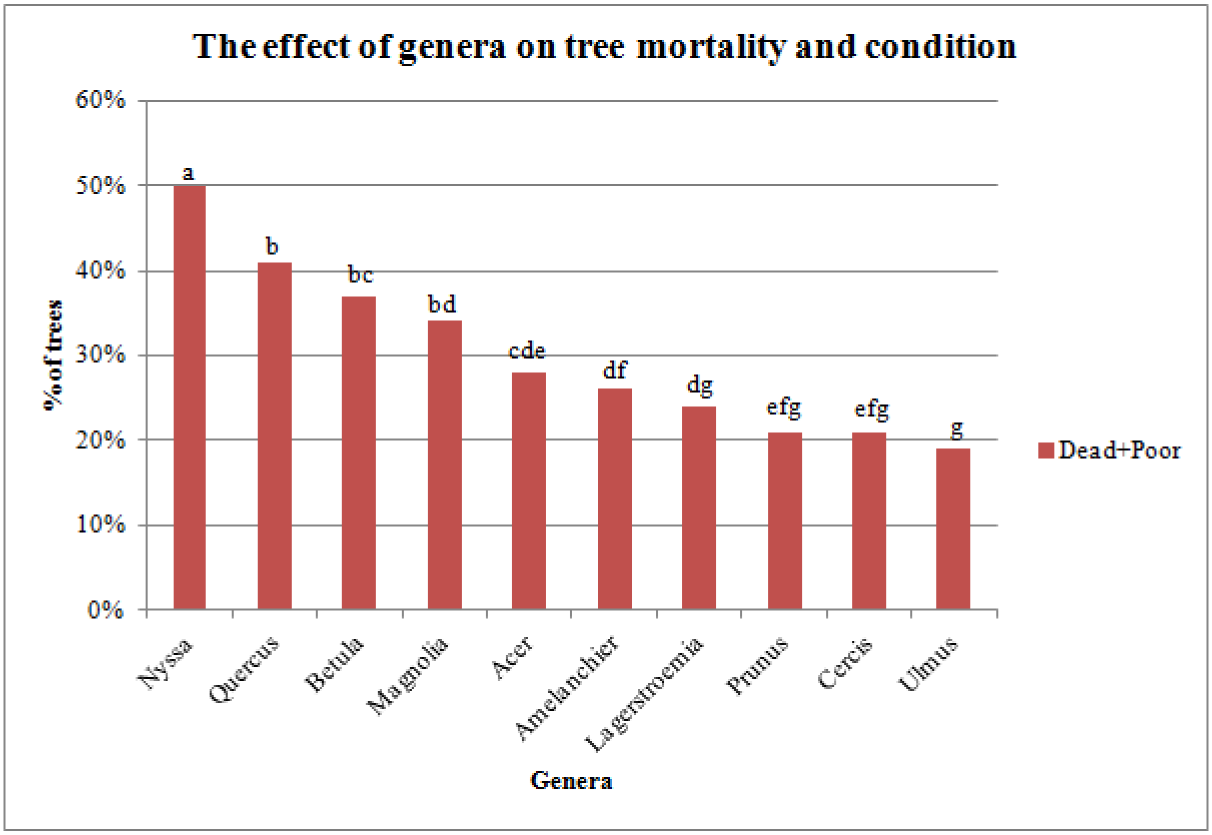


*Different letters above the bars indicate significant chi-square differences (p=0.05). CMM= Commercial (n=278); NPS= National Park Service (n=218); DPR= D.C. Parks and Recreation= (n=814); DCPS= D.C. Public Schools (n=505); PRV= Private (n=976); RSD= Residential (n=198); DDOT= D.C. Department of Transportation (n=781); SCH= School (n=40)

Genera

As mentioned in the methods section, only the top 10 genera with the highest number of plantings were considered in the chi-square analysis (Figure 3.11). Together these genera made up 2,929 observation or 72% of the total sampled inventory. *Nyssa* contained a significantly higher amount of dead+poor trees (50%) than the other nine genera. *Magnolia, Betula* and *Quercus* also had relatively high rates of dead+poor (34-41%) with no statistical difference found between the groups. The remaining five genera (*Acer, Amelanchier, Lagerstroemia, Prunus, Ceris, Ulmus*) were harder to statistically differentiate. Each of these groups contained percentages of dead+poor trees below the overall average found among the 10 genera groups (28%) (Figure 3.11, Appendix 7.8).

Figure 3.11: The percent of trees in the top 10 planted genera found to be in dead+poor condition for data collected in Washington, D.C. in summers 2008, 2009, 2010 and 2011. Genera categories were derived from species data collected by Casey Trees during planting.



*Different letters above the bars indicate significant chi-square differences (p=0.05). Nyssa= 213; Quercus= 384; Betula= 282; Magnolia= 232; Acer= 168; Amelanchier= 171; Lagerstroemia= 181; Prunus= 206; Cercis= 265; Ulmus= 823

Due to small sample sizes, other genera that contained higher or lower amounts of dead+poor trees then those observed above were not included in this analysis. However, percent dead+poor for each genera by individual planting years (2005, 2006, 2007 and 2008) and combined planting years can be found in Appendix 6.1-6.5.

<u>**Effect of Socioeconomic Variables on Tree Mortality and Condition**</u>

It is important to note that many of the socioeconomic factors were highly correlated. As one would expect median annual family income, median monthly rent, average house value and education level are all highly related. With the exception of median income (r= -0.52603) percent of youth (i.e., <25 years of age) also shows a strong correlation with each of these variables. Population density and percent unemployment show the weakest correlations with the other socioeconomic variables.

Due in part to the high degree of relatedness between each of the socioeconomic variables tree condition and mortality showed a strong correlation with six of the seven factors. Education level was the strongest predictor, with a correlation coefficient of -0.943. In other words, as education attainment increased (i.e., percent with a high school diploma or higher) the percent of dead+poor trees tended to decrease. The next strongest predictor of condition and mortality was age with an r= -0.840. As one would expect, average rent, median income and median value of house all closely followed. Population density showed the weakest, but still a moderately strong relationship with tree condition (r= -0.588). Interestingly, the correlation coefficient indicates that the percent of dead+poor trees tended to increase as population density decreased (Table 3.3).

Table 3.3: The results of the correlation analysis showing the relationship between each of the socioeconomic variables and the effect of these variables on tree condition and mortality, of trees from the Casey Tree inventory, Washington, D.C., observed in summers 2008, 2009, 2010 and 2011.

	POPDEN	INCOME	YOUTH	RENT	MHOUSE	UNEMP	EDU
INCOME	-0.37*						
YOUTH	0.07*	-0.53*					
RENT	-0.21*	0.78*	-0.46*				
HOUSE	-0.25*	0.91*	-0.39*	0.71*			
UNEMP	0.015	-0.25*	0.72*	-0.29*	-0.17*		
EDU	-0.36*	0.84*	-0.71*	0.72*	0.71*	-0.43*	
Dead+Poor	-0.59*	-0.78*	0.84*	-0.82*	-0.74*	0.75*	-0.94*

*p= 0.05; POPDEN= Population density; INCOME= Median annual family income; YOUTH= Percent of population less than 25 years of age; RENT= Median monthly rent; HOUSE= Average value of an owner occupied household; UNEMP= Percent unemployment; EDU= Percent of individuals with a high school diploma or higher

<u>Ecological Benefits Provided by Tree Plantings</u>

Carbon Storage and Sequestration

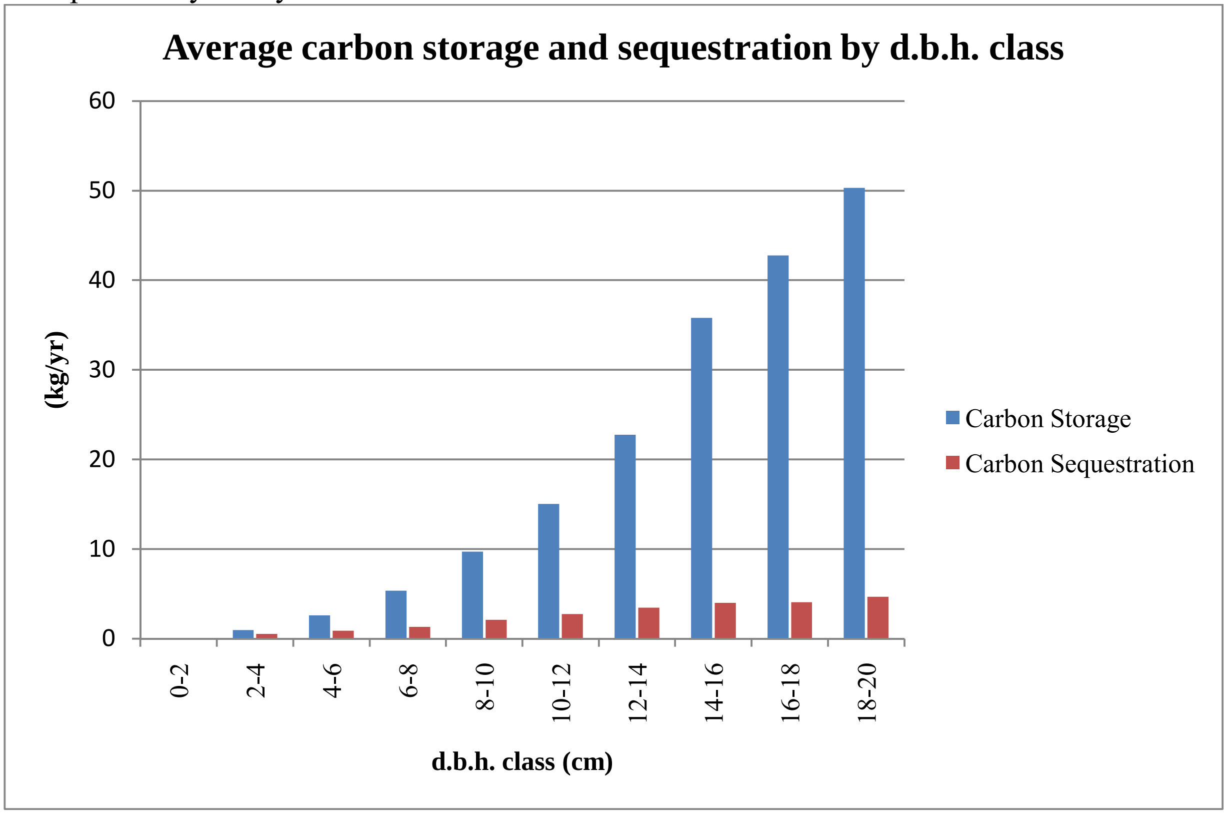
Total Carbon storage for trees observed in summer 2010 (i.e., planting years 2006 and 2007) totaled about 10,697 kg. The genera that contained the highest average storage amount per tree included *Juniperus* (19.2 kg), *Hamamelis* (14.1 kg), *Betula* (13.07 kg) and *Aesculus* (11.92 kg). Those genera that had the lowest average storage amount per tree were *Diospyros* (1.86 kg), *Nyssa* (2.00 kg), *Chionanthus* (2.62 kg) and *Ginkgo* (2.65 kg) (Appendix 3.1).

The amount of carbon sequestration for trees planted in years 2006 and 2007 was approximately 2,254 kg per year. The per tree average sequestration rate by genera did not vary significantly, with a range of only 0.60-2.46 kg/yr. Genera with the highest average sequestration rate per tree included *Acer* (2.46 kg/yr), *Prunus* (2.42 kg/yr), *Betula* (2.24 kg/yr) and *Lagerstroemia* (1.91 kg/yr). Genera the lowest average sequestration rate per tree were *Juniperus* (0.62 kg/yr), *Taxodium* (0.61 kg/yr), *Diospyros* (0.62 kg/yr) and *Pinus* (0.64 kg/yr) (Appendix 3.2).

Average carbon storage amounts increased substantially as tree diameter increased with around a 49 kg/yr difference between the smallest and the largest measured DBH Carbon sequestration show very little increase between the smallest and largest DBH groups and seem to level off quickly (Figure 3.12).

A total of 1,086 or 78% of the inventoried trees had DBH's between 2-10 cm (Figure 3.2). Carbon storage for these small trees is rather minimal (Figure 3.12). As trees mature carbon storage will increase substantially.

Figure 3.12: The average amount of carbon stored and sequestered by trees within each DBH class for trees observed in Washington, D.C. in summer 2010. Trees observed in this summer were planted by Casey Trees in 2006 and 2007.

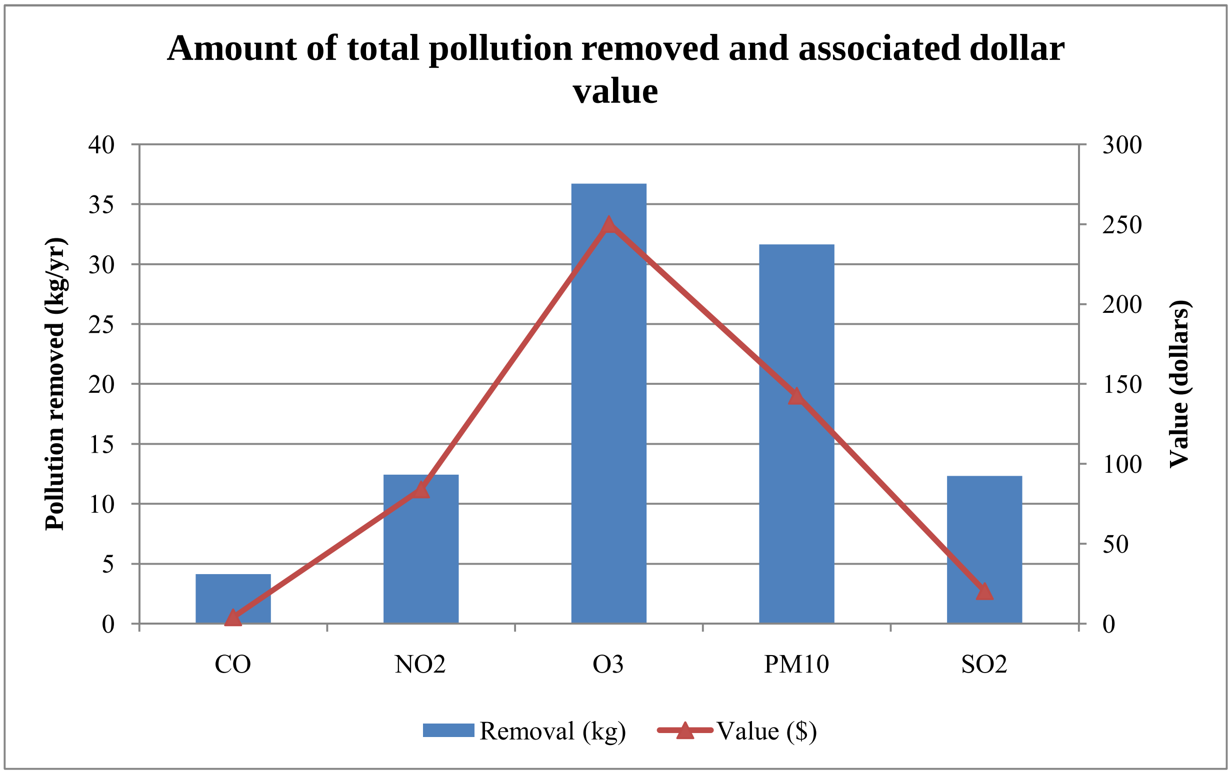


Pollution Abatement

Tree pollution removal for planting years 2006 and 2007 totaled around 97 kg/yr, which equates to about $520 in avoidance value[1] for CO, NO2, O3, PM10 and SO_2, combined. These values are minimal; however, one must consider the small number (n=1,391) and size of trees assessed. As these factors increase pollution abatement and associated values will inevitably increase. Ozone had the highest annual removal rates and associated monetary value with 37 kg/yr and $250, respectively. With a removal rate of only 4 kg/yr and an associated value of $4, CO had the lowest rates of annual removal and associated monetary value (Figure 3.13).

[1] Avoidance value- In terms of pollution, the value associated with the avoidance of harmful environmental or social effects that may be caused by higher levels of pollution. Often pollution removal values are associated with a reduction in health care costs (e.g., medical, hospitalization, health insurance permit costs).

Figure 3.13: The total amount of CO, NO_2, O_3, PM10 and SO_2 removed, along with the monetary value associated with the removal of each of these pollutants for trees observed in Washington, D.C. in summer 2010. Trees observed in this summer were planted by Casey Trees in 2006 and 2007.



Genera groups *Cedrus, Ulmus, Betula, Metasequoia* and *Liriodendron* showed the highest average removal rates per tree for each of the pollution types. *Cedrus* had a substantial higher average per tree removal rate than any other genera for CO, NO_2, O_3 and SO_2. PM10 varied slightly, with *Metasequoia* showing the highest average annual removal rate per tree (Appendix 4.1- 4.5).

Structural Value

Total structural or compensatory value[2] for planting years 2006 and 2007 was estimated at around $180,680 after outliers were removed. Average structural value per tree for the 45 genera ranged from around $41-475. Genera group *Metasequoia* had a substantially higher estimated average structural value per tree than any of the other groups ($475). After

Metasequoia, groups with the highest average value per tree included *Aseculus* ($259), *Hamamelis* ($245) and *Betula* ($223). Genera groups with the lowest average value were *Helesia* ($41), *Pistacia* ($46), *Syringa* ($51) and *Diospyros* ($51) (Appendix 5).

[2] Compensatory value- The value associated with replacement cost of a similar tree. Formulas used in the UFORE model are based on guidelines outlined by the Council of Tree and Landscape Appraisers (CTLA). They incorporate information on tree area, species, condition and location.

CHAPTER 4: DISCUSSION

Tree Mortality

Tree mortality in the first years of growth (i.e., 4 years post planting) ranged from 23-34%, with a 5-12% difference between the first and second sampling period. Comparing these rates with what has been reported in the literature can be difficult, as new tree mortality has been shown to be highly variable, with an estimated annual survival of between 2-65% found in previous studies (Foster and Blaine 1978, Sklar and Ames 1985, Nowak 1990, Roman 2006). Factors attributed to mortality rates were numerous, including differences in community participation, species, contractor, landuse and socioeconomic differences. The range of factors cited to contribute to tree mortality highlights the need for understanding local variation and how area-specific factors may interact to contribute to mortality.

Management of these factors is especially critical during tree establishment, which is defined as the four years following planting, when trees are most vulnerable to harsh environmental conditions (Richards 1979, Miller and Miller 1991, Roman 2006). If tree mortality can be reduced at a time when it is at its peak, average lifespan will increase substantially (Nowak 2004). Further supporting this conclusion is the finding that after the establishment period mortality rates have been shown to decrease substantially, typically under 5% (Impens and Delcarte 1979, Roman 2006).

Effect of Pre-Planning and Environmental Variables on Tree Mortality and Condition

The logistic regression model revealed that 7 of the 8 environmental and pre-planting variables had a significant effect on tree condition ($p \leq 0.0007$). These results highlight the complexity of the issue and the need for a multifaceted solution when managing a sustainable tree planting operation.

Nursery and Stock Type

The only factor assessed that was directly linked to the initial place of tree obtainment was nursery stock type (i.e., container grown or B&B). Although, B&B trees tend to be preferred over container grown trees, there are disadvantages that have been attributed to both stock types. One of the main problems cited with container grown trees is circling roots that conform to the shape of the container. These can ultimately lead to stem girdling, which can inhibit the uptake of water by vascular tissues (Lilly 2010). Conversely balled and burlapped trees, taken directly from the ground, can lose as much as 90% of their absorbing roots during the digging process (Lilly 2010).

There was no difference found in mortality related to stock type, so at least in this case each type of stock had an equal likelihood of survival. Balled and burlapped trees also tend to be slightly more expensive and harder to obtain (Tree Trust 2011). Thus, budgetary and availability constrains can serve as an important guideline when selection between the two stock types is necessary.

Since stock type was not an important component of tree mortality the significant differences in tree condition observed between the assessed nurseries are likely due to other unmeasured nursery-related variables. These factors may include differences in the holding time by contractor prior to nursery obtainment, differential levels of nursery care or differences in the planting or transport processes. Because these processes cannot be standardized between nurseries and information regarding initial tree care is typically unavailable, these factors may not be controlled. Thus, the best defense against nursery-related problems is likely careful tree selection and increased initial care to compensate for pre-existing issues.

In terms of selection, individual trees should be inspected at the nursery for signs of decreased health or vigor. The entire tree including, foliage, branches, trunk and roots should be inspected for discoloration or damage. The rooting system, which absorbs water and stores carbohydrates, is especially critical to new growth (Lilly 2010). Thus, special care should be given to inspecting both the color and growth pattern of roots. Trees that are container grown should be removed from the container to make sure that roots are not growing in a circular pattern around the stem. Plants should again be inspected for damage that may have occurred during transport prior to planting. Roots should be untangled prior to placement in assigned tree space. Other important considerations include factors such as planting depth and fill differences which may lead to excess or limited water availability. Extensive information on proper tree selection and installation can be found in a number of outside sources (e.g., Towbridge and Bassuk 2004, City of New York Parks and Recreation 2008, Appleton 2009, Lilly 2011).

Planting Time: Season and Year

Tree condition was variable between the assessed years (2005-2007) with mortality in the first few years ranging from 23-34%. This variability may be partially explained by the differences in seasonal planting by year. Overall, spring and summer showed a significantly higher rate of dead+poor trees then fall or winter. Years with the highest rates of dead+poor trees (2006 and 2007) also had a higher percent of trees planted during these months. Furthermore, year 2007, which showed the lowest percent of dead+poor trees, had between 5-15% fewer trees planted during spring and summer. Trees planted in 2008 were not included in this analysis due to a lack of a second sampling period. Strictly based on the findings, the high number of trees that were planted during spring/summer in 2008 may contribute to mortality rates near or above those observed in years 2005 and 2006 after the second sampling period is complete.

The differences found in seasonal associated mortality and condition are consistent with planting recommendations for the D.C. area. Planting time is critical, as high temperatures during spring and summer may limit water availability. Water has been cited as one of the most important environmental factors effecting new tree growth (Betty and Heckman 1981, Gilbertson and Bradshaw 1985). As long as temperature is at an appropriate threshold, lack of available water has been shown to have a linear relationship with root growth and development (Teskey and Hinckly 1981). The initial establishment of a functional rooting system is critical to carbohydrate storage and water uptake, which ultimately effects shoot elongation and overall tree growth (Lilly 2010).

Landuse and Space Type

Parks, recreation and open space and the institutional landuse categories showed the highest and lowest percentages of dead+poor trees, respectively. Although very few studies have assessed the effect of landuse on tree condition, my results are consistent with reported findings (Nowak et al. 2004). The effect of the surrounding area on tree condition is thought to be related to the level of care and intensity of use associated with a particular landuse. One theory suggests that trees in open land areas would tend to receive less care because “sense of ownership” is lacking (Sklar and Ames 1985, Nowak et al. 1990). In other words, open land areas tend to be more public, with less vested interest or incentive for individuals to care for trees. Government agencies are responsible for a large number of trees and may not have the resources necessary to provide the same level of care that is associated with more private landuses. Conversely, institutional land (e.g., universities, museums, churches, etc.) are less public and tend be under heavier surveillance. Furthermore, in these areas trees are likely to receive more consistent and professional-level care than trees planted in other landuse areas.

In this study the effect of space type (i.e., tree box, openland and continuous strip) on tree success may be more related to planting landuse and its associated level of care than to the actual effect space on tree growth. It is likely that trees are still too young and roots not large enough to be effected by space limitations. Thus, trees planted in tree box spaces likely showed a high percentage of dead+poor trees because these landuse areas tended to be highly public. In addition, open land spaces or parks that were more intensely used may have offered little incentive to provide tree care. However, this space type also included trees planted in residential and some private areas, which may help to explain why trees in open land spaces showed a slightly lower percentage of dead+poor than those planted in tree boxes. Continuous strip spaces had a significantly lower percentage of dead+poor then either of the other two space types. These spaces tended to be in neighborhoods that were less densely populated, ultimately contributing to a lower intensity of use. It is predicted that as trees grow and space becomes more of a limiting factor, those in open land spaces (that have made it past the initial establishment period) will begin to outperform those in the more confining continuous strip plots.

The results of both the landuse and space type data suggest that area-based management is an important consideration in enhancing the survival of newly planted trees. Open land or areas with a high intensity of use contained the highest percentages of dead+poor trees and should be given top priority in area-based management. In these areas, additional care by the planting group (e.g., supplemental watering, tree stakes, tree barriers to protect trunks and roots from vandalism, etc.) may greatly enhance new tree survival.

Jurisdiction

The effect of jurisdictional entity on tree mortality and condition can be explained by the same reasoning used in the landuse section. Commercial, the National Park Service (NPS) and D.C. Department of parks and recreation (DRP) had the highest rates of dead+poor trees. Commercial areas tend to be more public, thus sense of individual ownership and incentive to participate in tree care was likely lacking. In addition, these areas tend to have more traffic and a higher associated intensity of use, likely subjecting trees higher levels of compaction, vandalism and overall abuse. NPS and DPR jurisdictions are associated with trees planted in open land park spaces. As explained previously, these areas are public which tends to affect "sense of ownership" and desire to provide care.

It is important to note that the differences in tree health or mortality that exist between government agencies (NPS, DPR and DDOT) may be due to planting location rather than differing levels of care. For example, D.C. Department of Transportation (DDOT) is responsible for the care of street trees which tend to be within neighborhoods. It is possible that these trees have a lower number of dead+poor because community residents, who are interested in the aesthetic appeal of their neighborhoods, have more interest in caring for trees. In addition, it is likely that there is stronger call to action by community residents when trees are visibly declining.

The schools category (university/ private schools) showed a significantly lower percentage of dead+poor trees then the other 7 jurisdictional groups. These types of institutions are typically concerned with the overall maintenance of grounds and associated vegetation.

Professional crews are often hired to specifically care for trees. Thus, care of newly planted trees is often more regular and performed at a more professional level.

The commercial landuse showed a much higher percentage of dead+poor trees in the jurisdictional analysis than the landuse analysis. This difference, as well as other differences observed, may be due to errors or scale-level differences between the two data sets. The landuse data was obtained from D.C. government website. It is possible that these maps do not contain the level of resolution that is needed to effectively assess tree condition. In a recently published study on new tree mortality in New York City researchers found that 48% of tree sites visited had landuses that differed from those reported in city maps (Lu et al. 2010). With this said, field validation may be important in conducting future studies.

Genera

The factor level chi-square tests revealed that there was a significant effect of genera on tree mortality. Nyssa showed a significantly higher percentage of dead+poor trees then each of the other nine genera. The *Nyssa* genus was composed primarily of species *Nyssa sylvatica* (black gum). Due to *N. sylvatica's* overall tolerance to harsh environmental conditions, it has been suggested in a number of sources as being a viable choice for urban planting (Gilman and Watson 1994, Kuser 2000, Trowbridge and Bassuk 2004). It is thought to be resistant to most detrimental diseases and does well in excessively wet or dry environments (Gilman and Watson 1994). One limitation of this species is its sensitivity to high pH levels or soil alkalinity (Gilman and Watson 1994, Londo 2002). Urban soils may experience elevated pH due to a number of factors including, application of deicing salt, irrigation with calcium-enriched water, atmospheric pollution and the release of calcium from weathering of construction material (Craul 1992). Almost half of the soils in D.C. have been shown to have pH levels at or above 7, with some reaching as high as pH 9.0 (Craul 1992). Elevated soil pH can lead to nutrient deficiency and ultimately tree mortality by tying up essential nutrients such as iron (Fe), manganese (Mn) and phosphorus (P) (Konijnendijk et al. 2005). pH Testing strips are relatively affordable and can be used to test soil prior to planting of sensitive species. If pH is elevated, planting more tolerant species or applying pH lowering substances such as sphagnum peat, elemental sulfur, iron sulfate, acidifying nitrogen and organic mulches may help prevent related decline (Craul 1992, Mason 2008). Other factors that have been shown to affect the survival of *Nyssa sylvatica* include transplant shock and invasion by insects such as tupelo leaf miner (*Antispila nyssaefolia*) (Gilman and Watson 1994, USDA 2002).

The factor level chi-square analysis showed less statistical differentiation between the top performing species. *Lagerstromia, Prunus, Cercis* and *Ulmus* all had the lowest levels of dead+poor trees, with no statistical differences found between these genera. Ulmus was the best performing genera, with only 19% of individuals recorded as dead+poor. This is a major success considering that Dutch elm disease (DED) has killed around 25,000 American elms (*Ulmus americana*) in D.C. since the 1950's (U.S. Forest Service 2011). It also pays tribute to the effectiveness of the disease-tolerant elm cultivars (i.e., Jefferson, New Harmony, Princeton and Valley Forge) that have been utilized in Casey Trees' elm restoration program.

Additional environmental testing (e.g., assessment soil fertility, soil bulk density, plant physiological testing, etc.) is needed to determine exact causes of tree mortality and condition. Furthermore, this information may be helpful in explaining why significant difference exist between the assessed genera.

Effect of Socioeconomics Variables on Tree Mortality and Condition

The correlation analyses revealed a strong linear relationship ($r>0.74$) between tree condition and 6 of the 7 socioeconomic variables. As mentioned previously, to allow for comparison, the index of variables were obtained from a similar study conducted in Oakland, CA (Nowak 1990). The Oakland study showed a similar positive relationship between socioeconomic variables and tree condition; however, the number and strength of linear associations was significantly higher in this study. Due to the high level of correlation between the socioeconomic variables in D.C., it is logical to expect that many of the factors would show a similar correlation coefficient value when compared to tree condition.

Although it can be assumed that areas of low socioeconomic status tend to have less available resources, neither of these studies was able to determine the exact cause(s) of mortality. For example, is tree condition more related to a lack of physical resources and/or is there a need for more educational outreach. Little to no research has been done to address this concern; however, answering these questions would be an important component to fine-tuning management practices. Qualitative studies (e.g., surveys and/or interviews) may help extract details that cannot be obtained through quantitative analysis alone.

Management Recommendations

A number of management recommendations were discussed in the previous sections. The following will serve an overview and summary of the factors that should be considered when managing a sustainable tree planting operation. First, nursery or initial site of tree obtainment should be addressed. However, many factors associated with nursery related problems are unknown and cannot be controlled (e.g., holding time by contractor or nursery, nursery care, etc.). Thus, management efforts should include careful selection of visibly health trees.

Inspection of the total tree, including roots, trunk, branches and foliage is important in determining overall health. After the selection process, management and oversight should be focused on ensuring successful transport and planting of newly obtained trees.

In addition, time of planting is a critical pre-planting management consideration. Based on this study, in Washington, D.C., the best time to plant a tree is fall and early winter months. This is likely true of surrounding cities, which tend to have similar climatic conditions. The exact time of planting will vary by region, as temperature and precipitation changes. In addition, differences in tolerance associated with species/genus may affect planting time. Awareness of the needs associated with a species/genus is important to fine tuning management efforts. Slight and inexpensive changes in planting procedures (e.g., adjusting pH, planting depth, etc.) may greatly improve the successful establishment and longevity of an urban tree.

Lastly, differences in the area surrounding a tree (i.e., landuse, socioeconomics) need to be addressed, as these factors have been shown to have a significant effect on new tree success. Landuse and socioeconomic differences can affect the intensity of use and level of care a tree receives. Trees in open land and public areas tend to have higher rates of mortality and should be given priority in area-based management. Management efforts in these areas may include supplemental watering, trunk guards or tree stakes to protect against vandalism, barriers or fences around rooting zones to decrease soil compaction, etc. Incorporating these same measures in lower socioeconomic areas, which may lack the resources needed to care for trees, may also help improve overall tree success. In addition, providing educational outreach on proper care may in lower socioeconomic areas may serve as an effective means of reducing new tree mortality and enhancing the sustainability of long-term ecological benefits.

Ecological Benefits Provided by the Tree Plantings

Olivier et al. 2011 found that in 2010 carbon dioxide levels increased by more than 5%, which is unprecedented in the last 2 decades (Olivier et al. 2011). As human populations grows and with it energy consumption, (e.g., industrial processes, increased combustion of fossil fuels used in transportation, large scale food production, etc.) the mitigating potential of trees becomes increasingly important. Although this study showed minimal benefits in terms of CO_2 storage and sequestration and pollution abatement, one must be aware of several limiting factors when considering the results. Due to time and budget constrains the study included a rather small sample size measured over a short period of time. In addition, the trees in this study were still exceedingly small and their ability to mitigate CO_2 and pollution is limited. Most trees were found to be between the 4-10 cm in diameter, which was shown to produce very little benefit per tree in terms of carbon storage and sequestration. As tree diameters increase and management practices improve, benefits will likely increase substantially. A study by Nowak and Crane found that large trees (i.e., >77 cm diameter) sequester 90 times and store 1000 times more CO_2 than small trees (i.e., <8 cm) (Nowak and Crane 2002).

Structural or compensatory values were much higher than those associated with CO_2 or pollution removal. This illustrates the important point that trees accrue value in numerous ways. Furthermore, there are a number of services that trees provide beyond those reviewed in this study (e.g., stormwater abatement, wildlife habitat, social, health, aesthetic, etc.). Many of these are hard to measure quantitatively and assigning a monetary value can be difficult. Nevertheless, these benefits are valuable and exceedingly important to the functioning of urban areas.

Limitations and Suggested Study Design Improvements

Although a number of general management recommendations can be draw from this study, understanding the causes of tree mortality at a finer scale requires further study of interactions between assessed variables. To understand interactions, factors shown to have an effect on tree condition will need to be controlled to limit variation. The first step in this process should be controlling large scale or landscape-level variation through a stratified sampling procedure. The two landscape-level factors that were assessed in this study included landuse and socioeconomics. These factors can ultimately be combined to form smaller subset sampling groups. For example, within each lager pre-determined socioeconomic grouping, landuse type subsets can be created. As mentioned previously, if city landuse maps are utilized, field validation may be needed to confirm errors or scale differences that exist at a tree level. After the landscape is divided into sampling subsets, previously collected tree-level data can be used to further control variation within each of these groups. Factors included in this study that should be controlled include genera and planting time (i.e., season and year). Once new groups are formed, trees should be selected within these groups at random. Additional environmental testing (e.g., soil bulk density, soil fertility) and removal of sites that are significantly different may help further control variation.

Other factors assessed in this study which may have limited use in future studies include nursery, stock type, space type and jurisdiction. Despite differences that may exist between nurseries, there are still many unknowns (e.g., differences in initial care). Thus, conclusions regarding this factor tend to be rather limited. In this study stock type had very little effect on tree condition and may not be a significant factor in overall tree success. Both jurisdiction and space type seemed to be strongly correlated with landuse. Depending on the needs of the organization, results from landuse stratification may provide enough overall detail. Direct effect of space type on tree growth and condition may become more important as rooting space becomes limited. In this sense, initial control of space type differences are likely unnecessary; however, it is important that within each larger landuse area overall space type does not vary substantially. For example, the condition of two trees planted within the same landuse may vary if the tree is planted on public vs. private land. Furthermore, a street tree within a residential area may experience higher levels of pollution (e.g., deicing salt, transportation related pollution) and possibly less care then those planted on private property.

Setting up a stratified, more controlled experiment is only a first step. If differences exist between stratified groups after environmental (e.g., planting time/ space type) and tree-based (e.g., genera/species) variables are controlled, further analysis may be helpful in answering why patterns are occurring. As mentioned previously, qualitative surveys and interviews may help add a level of understanding that cannot be obtained through quantitative data collection.

Conclusions

Urban trees provide numerous benefits, beyond those that were measured in this study. Due to the small number of the trees measured, average benefits were shown to be minimal; however, they are likely to increase significantly as trees mature with age. Mortality rates in the first few years of growth were substantial (23-34%), indicating the potential for improved management of urban tree mortality when it is at its peak will enhance the long-term production of tree-based benefits (Romen 2006).

Unfortunately, understanding and managing the numerous factors (e.g., environmental, socioeconomic) that contribute to new tree mortality can be exceeding complex. A number management recommendation can be taken from this study and applied broadly. For example, in general, trees in public, open land or lower socioeconomic areas should be given high priority in area-based management. Understanding interactions between these factors adds a layer of complexity, but may provide additional fine-scale details that are necessary for more effective management. For instance, trees in residential areas tend to have lower mortality rates than those planted in open land spaces; however, mortality within these sites may still vary by planting space location (e.g., street tree vs. residential property).

Understanding tree condition at a finer scale requires study of interactions and ultimately control of factor-level variation. This can be difficult, as variation in natural environments can be hard to delineate and choosing the correct scale of study can further complicates issues. In addition, numerous factors affecting mortality contribute to the large amount stratification that is needed to understand interactions. As stratification increases, experimental design may become exceeding complex. Stratification may also significantly limit experimental units that are needed to meet sampling demands (e.g., consistent age of trees). Because many initial tree-based details are known and can be standardized, the Casey Trees data set will be highly useful in a large scale stratified study once the number of observations is large enough to meet sampling needs.

In addition to variation caused by interactions, it is important to note that results may be further influenced by area-specific differences. For example, environmental history may influence soil, prevalence or type of pollution. Furthermore, cultural differences may influence level or type of care received. Thus, effective management requires a deep understanding of local variation. Additional environmental and qualitative data collection may be needed to fully understand the influence of these variables.

Much work still needs to done in order to understand how factors affecting urban tree mortality and condition interact at both larger and more local scales. Thus, the immediate goal in urban tree management should not be perfection, but rather adaptability and the implementation of the best practices while our understanding of urban tree mortality continues to evolve.

Appendix 1: Casey Trees Community Tree Planting (CTP) Program Application Form

Below is the Casey Trees Flagship Community Tree Planting (CTP) program application form, which can be found on Casey Trees' official website. The application form includes maintenance requirements that applicants must agree to before planting begins. Appropriate species selection and location details are discussed with Casey Trees staff and volunteers after an application is reviewed and selected.

about

Casey Trees **Community Tree Planting** (CTP) Program, established in 2005, is a grassroots approach to planting trees in neighborhoods throughout the District of Columbia. Individuals and groups interested in adding trees – **ten or more** – to their apartment complex, school, church, park, synagogue, or even private yard may apply.

Applicants propose a planting site – in DC only – and locations for the trees. Successful applicants are assigned a Casey Trees-trained Lead Citizen Forester as a technical advisor to help applicants determine which tree species to plant and where, and develop a planting plan and maintenance schedule. Casey Trees provides onsite planting help AND all the required tools and trees.

The best part – it's FREE!

Applicants must:

- Propose locations for a minimum of ten (10) trees.
- Obtain permission of all property owners where trees will be planted.
- Agree to a post planting, two-year maintenance plan for the trees that includes weekly watering.
- Attend an orientation meeting.
- Provide lunch (i.e. pizza/bbq) to volunteers immediately following the planting.

deadlines

CTP applications are accepted year round.

Submission Window	**Eligible Planting Season**
June 15 - November 30	Spring (March - May)
December 1- June 14	Fall (October - December)

Note - To be eligible for a specific planting season, applications must be received during the corresponding submission window.

submission instructions:

Applications may be mailed, faxed, or emailed.

M: Casey Trees
Department of Tree Planting
3030 12th Street NE
Washington, DC 20017

E: friends@caseytrees.org

F: 202.833.4092

questions?

Jim Woodworth - Director of Tree Planting
jwoodworth@caseytrees.org
202 349 1904

Project Location

Street Address ____ Ward ____

Requesting Group

Name ____

Type (i.e. civic association, youth shelter) ____

Project Organizer

Name ____

Mailing Address ____

City ____ ST ____ Postal Code ____

Daytime Phone ____ Evening Phone ____

Email ____

Goals of Project

What are the goals of your project?

Number of Trees

Enter the number of trees for each type of location.

___ Residential/housing
___ Apartment/condo/coop
___ Park/Open Space
___ School
___ Street*
*American elm - approved locations only
___ Community garden**
(**can include fruit trees)
___ Religious institution
___ Commercial/business
___ Other

Site Description

Attach a map - can be a sketch - of the proposed planting site indicating locations of new trees. Include street intersections, addresses, and/or landmarks. Photos are helpful.

Appendix 2: Casey Trees' Species List for the Washington D.C. Area

Below is a list of tree species that Casey Trees has pre-approved for their planting programs. The species included have been found to thrive in urban areas and under the climatic conditions that are present in Washington, D.C.

Small/Flowering Species

- Serviceberry (Amelanchier)*
- American Hornbeam (Carpinus caroliniana)*
- Redbud (Cercis canadensis)*
- Crapemyrtle (Lagerstroemia indica)
- Sweet Bay Magnolia (Magnolia virginiana)*
- American Hophornbeam (Ostrya virginiana)*

Medium Species

- River Birch (Betula nigra)*
- Katsura Tree (Cercidiphyllum japonicum)
- American Yellowwood (Cladrastis kentukea)*
- Honeylocust (Gleditsia triacanthos)*
- Yoshino Cherry (Prunus xyedoensis)

Evergreen Species

- Deodar Cedar (Cedrus deodara)
- Japanese Cryptomeria (Cryptomeria Japonica)
- Eastern Redcedar (Juniperus virginiana)*
- Southern Magnolia (Magnolia grandiflora)*
- White pine (Pinus strobes)*

Large/Shade Species

- American Elm
  - Jefferson
  - New Harmony
  - Princeton
  - Valley Forge
- Red Maple (Acer rubrum)*
- Hackberry (Celtis occidentalis)*
- Ginkgo (Ginkgo biloba)
- Sweetgum (Liquidambar styraciflua)*
- Tuliptree (Liriodendron tulipifera)*
- Black Gum (Nyssa sylvatica)*
- Chinese Pistache (Pistacia chinensis)
- London Planetree (Platanus xacerifolia)
- Swamp White Oak (Quercus bicolor)*
- Overcup Oak (Quercus lyrata)*
- Willow Oak (Quercus phellos)*
- Red Oak (Quercus rubra)*
- Littleleaf Linden (Tilia cordata)
- Silver Linden (Tilia tomentosa)
- Chinese Elm (Ulmus parvifolia)

Appendix 3: Carbon Storage and Sequestration Rates by Genus

The tables below (3.1 and 3.2) show the total number of trees sampled within each genus and the associated carbon storage and sequestration rates for trees observed in Washington, D.C. in summers 2010. To allow for comparison, the last column of each table shows the average per tree carbon storage and sequestration rate by genus. Finally, the tables are sorted from high to low average per tree carbon stored/ sequestered by genus.

3.1: Carbon Storage

Genera	# of obs.	Carbon Storage (kg)	Avg. Carbon Storage (kg)
Juniperus	3	57.6	19.2
Hamamelis	9	126.94	14.1
Betula	74	967.06	13.07
Aesculus	2	23.63	11.82
Acer	39	452.57	11.6
Cedrus	6	69.17	11.53
Prunus	77	877.99	11.4
Metasequoia	4	43.1	10.78
Picea	7	74.22	10.6
Cladrastis	15	156.14	10.41
Cotinus	3	29.4	9.8
Fagus	5	47.66	9.53
Platanus	45	421.14	9.36
Styrax	2	18.42	9.21
Lagerstroemia	93	836.28	8.99
Ilex	47	405.29	8.62
Quercus	79	642.28	8.13
Parrotia	3	24.02	8.01
Cercidiphyllum	6	46.73	7.79
Magnolia	94	710.72	7.56
Ulmus	316	2364.25	7.51
Liriodendron	3	22.34	7.45
Cercis	130	829.22	6.38
Gymnocladus	2	12.61	6.31
Amelancier	64	395.02	6.17
Malus	6	34.48	5.75
Carpinus	19	101.14	5.32
Gleditsia	17	89.97	5.29
Celtis	7	36.81	5.26
Tilia	13	67.6	5.2
Koelreuteria	9	44.46	4.94
Taxodium	13	62.93	4.84
Cornus	44	206.07	4.68
Pinus	5	23.23	4.65
Syringa	5	20.79	4.16
Liquidambar	15	62.28	4.15

Cyptomeria	1	3.51	3.51
Helesia	1	3.49	3.49
Ostrya	17	53.33	3.14
Pistacia	3	8.47	2.82
Ginkgo	15	39.8	2.65
Chionanthus	41	107.37	2.62
Nyssa	36	71.9	2
Diospyros	3	5.58	1.86

3.2: Carbon Sequestration

Genera	# of obs.	Carbon Seq. (kg/yr)	Avg. Carbon Seq. (kg/yr)
Acer	39	95.95	2.46
Prunus	77	186.53	2.42
Betula	74	165.51	2.24
Lagerstroemia	93	177.22	1.91
Fagus	5	9.5	1.9
Ulmus	316	591.62	1.88
Cladrastis	15	27.86	1.86
Cercidiphyllum	6	11	1.83
Aesculus	2	3.63	1.82
Hamamelis	9	15.28	1.7
Cotinus	3	4.95	1.65
Platanus	45	73.09	1.62
Styrax	2	3.17	1.59
Picea	7	10.98	1.57
Magnolia	94	141.07	1.5
Quercus	79	118.02	1.49
Celtis	7	10.28	1.47
Malus	6	8.43	1.41
Cercis	130	179.88	1.38
Carpinus	19	25.79	1.36
Ilex	47	63.52	1.35
Liriodendron	3	4.02	1.34
Tilia	13	17.04	1.31
Gymnocladus	2	2.6	1.3
Gleditsia	17	21.85	1.29
Cornus	44	54.79	1.25
Metasequoia	4	4.95	1.24
Amelancier	64	79.56	1.24
Ginkgo	15	16.26	1.08
Parrotia	3	2.99	1
Koelreuteria	9	9.02	1
Syringa	5	4.9	0.98
Helesia	1	0.97	0.97
Chionanthus	41	36.02	0.88
Pistacia	3	2.64	0.88
Ostrya	17	14.29	0.84

Cyptomeria	1	0.82	0.82
Nyssa	36	28.64	0.8
Cedrus	6	4.24	0.71
Liquidambar	15	10.41	0.69
Pinus	5	3.18	0.64
Diospyros	3	1.86	0.62
Taxodium	13	7.95	0.61
Juniperus	3	1.79	0.6

Appendix 4: Pollution Removal and Associated Value ($) by Genus

The tables below (4.1, 4.2, 4.3, 4.4 and 4.5) show the total number of individual trees sampled within each genus, the total removal rates and associated value in dollars for CO_2, NO_2, O_3, PM10 and SO_2 removal for trees observed in Washington, D.C. in summers 2010. To allow for comparison, the fourth and sixth columns show the average per tree removal rates and the associated average per tree dollar value by genus. Finally, the tables are sorted from high to low average per tree pollution removal amount by genus.

4.1: CO_2

Genera	# of obs.	Total CO (g/yr)	Avg. CO (g/yr)	Total value ($)	Avg. ($)
Cedrus	5	67.75	13.55	0.06	0.01
Ulmus	315	1820.46	5.78	1.62	0.01
Betula	72	385.46	5.35	0.35	0
Liriodendron	3	14.61	4.87	0.01	0
Picea	7	34	4.86	0.03	0
Cladastis	15	68.82	4.59	0.06	0
Gymnocladus	2	7.61	3.81	0.01	0
Prunus	76	276.14	3.63	0.25	0
Quercus	79	282.06	3.57	0.25	0
Acer	39	135.1	3.46	0.12	0
Styrax	2	6.4	3.2	0.01	0
Cercidiphyllum	6	18.15	3.02	0.02	0
Cryptomeria	1	2.81	2.81	0	0
Platanus	45	125.59	2.79	0.11	0
Tilia	13	35.99	2.77	0.03	0
Pinus	5	13.78	2.76	0.01	0
Aesculus	2	4.89	2.45	0	0
Malus	6	14.71	2.45	0.01	0
Celtis	7	15.85	2.26	0.01	0
Lagerstroemia	93	190.47	2.05	0.17	0
Ilex	47	93.93	2	0.08	0
Pistacia	1	1.94	1.94	0	0
Diospyros	3	5.68	1.89	0.01	0
Gleditsia	18	32.25	1.79	0.03	0
Fagus	5	8.85	1.77	0.01	0
Magnolia	94	152.78	1.63	0.14	0
Koelreuteria	9	13.92	1.55	0.01	0
Juniperus	2	2.98	1.49	0	0
Cotinus	3	4.27	1.42	0	0
Carpinus	19	25.68	1.35	0.02	0
Amelanchier	64	81.71	1.28	0.07	0
Liquidambar	15	18.48	1.23	0.02	0
Cornus	44	53.57	1.22	0.05	0
Hamamelis	9	7.2	0.8	0.01	0
Ostrya	17	13.45	0.79	0.01	0

Nyssa	36	21.15	0.59	0.02	0
Cercis	130	64.82	0.5	0.28	0
Ginko	15	7.49	0.5	0.01	0
Syringa	5	1.88	0.38	0	0
Chionanthus	41	0	0	0.03	0
Halesia	1	0	0	0	0
Matasequoia	5	0	0	0.02	0
Parrotia	3	0	0	0	0
Taxodium	12	0	0	0.05	0

4.2: NO_2

Genera	# of obs.	Total NO_2 (g/yr)	Avg. NO_2 (g/yr)	Total value ($)	Avg. ($)
Cedrus	5	186.82	37.36	1.26	0.25
Ulmus	315	5019.69	15.94	33.89	0.11
Matasequoia	5	74.59	14.92	0.5	0.1
Betula	72	1068.06	14.83	7.21	0.1
Liriodendron	3	40.27	13.42	0.27	0.09
Picea	7	93.75	13.39	0.63	0.09
Taxodium	12	160.48	13.37	1.08	0.09
Cladastis	15	189.75	12.65	1.28	0.09
Gymnocladus	2	20.99	10.49	0.14	0.07
Prunus	76	774.29	10.19	5.23	0.07
Quercus	79	777.77	9.85	5.25	0.07
Acer	39	372.53	9.55	2.52	0.06
Styrax	2	17.64	8.82	0.12	0.06
Cercidiphyllum	6	50.04	8.34	0.34	0.06
Cryptomeria	1	7.74	7.74	0.05	0.05
Platanus	45	346.29	7.7	2.34	0.05
Tilia	13	99.24	7.63	0.67	0.05
Pinus	5	37.99	7.6	0.26	0.05
Malus	6	40.56	6.76	0.27	0.05
Aesculus	2	13.49	6.74	0.09	0.05
Cercis	130	855.28	6.58	5.78	0.04
Celtis	7	43.72	6.25	0.3	0.04
Lagerstroemia	93	525.2	5.65	3.55	0.04
Ilex	47	258.99	5.51	1.75	0.04
Pistacia	1	5.34	5.34	0.04	0.04
Diospyros	3	15.67	5.22	0.11	0.04
Gleditsia	18	88.94	4.94	0.6	0.03
Fagus	5	24.41	4.88	0.16	0.03
Magnolia	94	421.26	4.48	2.84	0.03
Koelreuteria	9	38.39	4.27	0.26	0.03
Juniperus	2	8.2	4.1	0.06	0.03
Cotinus	3	11.76	3.92	0.08	0.03
Carpinus	19	70.8	3.73	0.48	0.03
Amelanchier	64	225.3	3.52	1.52	0.02
Liquidambar	15	50.96	3.4	0.34	0.02
Cornus	44	147.68	3.36	1	0.02
Hamamelis	9	27.15	3.02	0.18	0.02

Chionanthus	41	95.98	2.34	0.65	0.02
Ostrya	17	37.08	2.18	0.25	0.01
Parrotia	3	5.92	1.97	0.04	0.01
Nyssa	36	58.31	1.62	0.39	0.01
Halesia	1	1.6	1.6	0.01	0.01
Ginko	15	20.65	1.38	0.14	0.01
Syringa	5	5.18	1.04	0.04	0.01

4.3: O_3

Genera	# of obs.	Total O_3 (g/yr)	Avg. O_3 (g/yr)	Total value ($)	Avg. ($)
Cedrus	5	598.06	119.61	3.76	0.75
Ulmus	315	16069.48	51.01	100.97	0.32
Matasequoia	5	238.77	47.75	1.5	0.3
Betula	72	3402.52	47.26	21.48	0.3
Liriodendron	3	128.92	42.97	0.81	0.27
Picea	7	300.11	42.87	1.89	0.27
Cladastis	15	607.45	40.5	3.82	0.25
Gymnocladus	2	67.18	33.59	0.42	0.21
Prunus	76	2437.53	32.07	15.57	0.2
Quercus	79	2489.86	31.52	15.64	0.2
Acer	39	1192.58	30.58	7.49	0.19
Styrax	2	56.46	28.23	0.35	0.18
Cercidiphyllum	6	160.18	26.7	1.01	0.17
Cryptomeria	1	24.79	24.79	0.16	0.16
Platanus	45	1108.58	24.64	6.97	0.15
Tilia	13	317.68	24.44	2	0.15
Pinus	5	121.62	24.32	0.76	0.15
Malus	6	129.85	21.64	0.82	0.14
Aesculus	2	43.17	21.59	0.27	0.14
Celtis	7	139.95	19.99	0.88	0.13
Lagerstroemia	93	1681.31	18.08	10.56	0.11
Ilex	47	829.09	17.64	5.21	0.11
Pistacia	1	17.1	17.1	0.11	0.11
Diospyros	3	50.16	16.72	0.32	0.11
Gleditsia	18	284.72	15.82	1.79	0.1
Fagus	5	78.14	15.63	0.49	0.1
Magnolia	94	1348.59	14.35	8.47	0.09
Koelreuteria	9	122.89	13.65	0.77	0.09
Juniperus	2	26.26	13.13	0.17	0.08
Cotinus	3	37.66	12.55	0.24	0.08
Carpinus	19	226.67	11.93	1.42	0.07
Amelanchier	64	721.25	11.27	4.53	0.07
Liquidambar	15	163.13	10.88	1.02	0.07
Cornus	44	472.79	10.75	2.97	0.07
Hamamelis	9	63.56	7.06	0.55	0.06
Ostrya	17	118.69	6.98	0.75	0.04
Nyssa	36	186.66	5.18	1.17	0.03

Ginko	15	66.1	4.41	0.42	0.03
Cercis	130	572.17	4.4	17.2	0.13
Syringa	5	16.59	3.32	0.1	0.02
Chionanthus	41	0	0	1.93	0.05
Halesia	1	0	0	0.03	0.03
Parrotia	3	0	0	0.12	0.04
Taxodium	12	0	0	3.23	0.27

4.4: PM10

Genera	# obs.	Total PM10 (g/yr)	Avg. PM10 (g/yr)	Total ($)	Avg. ($)
Matasequoia	5	222.29	44.46	1	0.2
Liriodendron	3	122.38	40.79	0.55	0.18
Betula	72	2692.08	37.39	12.14	0.17
Ulmus	315	11127.89	35.33	50.16	0.16
Cladastis	15	503.47	33.56	2.27	0.15
Platanus	45	1453.52	32.3	6.55	0.15
Prunus	76	2162.84	28.46	9.75	0.13
Acer	39	1100.41	28.22	4.96	0.13
Gymnocladus	2	56.14	28.07	0.25	0.13
Cedrus	5	131.12	26.22	0.59	0.12
Quercus	79	1882.21	23.83	8.49	0.11
Styrax	2	46.85	23.42	0.21	0.11
Celtis	7	156.36	22.34	0.71	0.1
Cercis	130	2896.97	22.28	13.06	0.1
Taxodium	12	263.47	21.96	1.19	0.1
Fagus	5	109.6	21.92	0.49	0.1
Cercidiphyllum	6	126.55	21.09	0.57	0.1
Tilia	13	270.15	20.78	1.22	0.09
Aesculus	2	35.36	17.68	0.16	0.08
Pinus	5	83.86	16.77	0.38	0.08
Malus	6	98.7	16.45	0.45	0.07
Lagerstroemia	93	1511.96	16.26	6.82	0.07
Gleditsia	18	285.78	15.88	1.29	0.07
Diospyros	3	46.28	15.43	0.21	0.07
Liquidambar	15	220.53	14.7	0.99	0.07
Pistacia	1	14.02	14.02	0.06	0.06
Picea	7	97.9	13.99	0.44	0.06
Cornus	44	556.64	12.65	2.51	0.06
Cryptomeria	1	12.33	12.33	0.06	0.06
Koelreuteria	9	109.73	12.19	0.49	0.05
Carpinus	19	227.69	11.98	1.03	0.05
Hamamelis	9	106.4	11.82	0.48	0.05
Amelanchier	64	748.63	11.7	3.37	0.05
Nyssa	36	373.31	10.37	1.68	0.05
Cotinus	3	30.72	10.24	0.14	0.05
Magnolia	94	831.93	8.85	3.75	0.04
Ilex	47	388.45	8.26	1.75	0.04

Chionanthus	41	282.04	6.88	1.27	0.03
Ginko	15	102.67	6.84	0.46	0.03
Ostrya	17	113.01	6.65	0.51	0.03
Halesia	1	6.13	6.13	0.03	0.03
Parrotia	3	15.54	5.18	0.07	0.02
Juniperus	2	6.48	3.24	0.03	0.01
Syringa	5	12.36	2.47	0.06	0.01

4.5: SO_2

Genera	# obs.	Total SO_2 (g/yr)	Avg. SO_2 (g/yr)	Total ($)	Avg. ($)
Cedrus	5	185.01	37	0.31	0.06
Ulmus	315	4971.03	15.78	8.22	0.03
Matasequoia	5	73.86	14.77	0.12	0.02
Betula	72	1057.7	14.69	1.75	0.02
Liriodendron	3	39.88	13.29	0.07	0.02
Picea	7	92.84	13.26	0.15	0.02
Taxodium	12	158.92	13.24	0.26	0.02
Cladastis	15	187.91	12.53	0.31	0.02
Gymnocladus	2	20.78	10.39	0.03	0.02
Prunus	76	766.79	10.09	1.27	0.02
Quercus	79	770.23	9.75	1.27	0.02
Acer	39	368.92	9.46	0.61	0.02
Styrax	2	17.47	8.73	0.03	0.01
Cercidiphyllum	6	49.55	8.26	0.08	0.01
Cryptomeria	1	7.67	7.67	0.01	0.01
Platanus	45	342.93	7.62	0.57	0.01
Tilia	13	98.28	7.56	0.16	0.01
Pinus	5	37.62	7.52	0.06	0.01
Malus	6	40.17	6.7	0.07	0.01
Aesculus	2	13.36	6.68	0.02	0.01
Cercis	130	847	6.52	1.4	0.01
Celtis	7	43.29	6.18	0.07	0.01
Lagerstroemia	93	520.1	5.59	0.86	0.01
Ilex	47	256.47	5.46	0.42	0.01
Pistacia	1	5.29	5.29	0.01	0.01
Diospyros	3	15.52	5.17	0.03	0.01
Gleditsia	18	88.08	4.89	0.15	0.01
Fagus	5	24.17	4.83	0.04	0.01
Magnolia	94	417.18	4.44	0.69	0.01
Koelreuteria	9	38.01	4.22	0.06	0.01
Juniperus	2	8.12	4.06	0.01	0.01
Cotinus	3	11.65	3.88	0.02	0.01
Carpinus	19	70.12	3.69	0.12	0.01
Amelanchier	64	223.12	3.49	0.37	0.01
Liquidambar	15	50.47	3.36	0.08	0.01
Cornus	44	146.26	3.32	0.24	0.01
Hamamelis	9	26.88	2.99	0.04	0

Chionanthus	41	95.05	2.32	0.16	0
Ostrya	17	36.72	2.16	0.06	0
Parrotia	3	5.87	1.96	0.01	0
Nyssa	36	57.74	1.6	0.1	0
Halesia	1	1.58	1.58	0	0
Ginko	15	20.45	1.36	0.03	0
Syringa	5	5.13	1.03	0.01	0

Appendix 5: Structural Values by Genus

The table below shows the total number of individual trees sampled within each genus and total structural value in dollars for trees observed in Washington, D.C. in summers 2010. To allow for comparison, the last column shows the average per tree dollar value by genus. Finally, the table is sorted high to low average per tree structural value by genus.

Genera	# of obs.	Value ($)	Avg. Value ($)
Metasequoia	4	1901	475.25
Aesculus	2	518	259
Hamamelis	9	2212	245.78
Betula	74	16528	223.35
Picea	7	1407	201
Quercus	79	15288	193.52
Cotinus	3	574	191.33
Styrax	2	373	186.5
Cladrastis	15	2666	177.73
Acer	39	6499	166.64
Liriodendron	3	470	156.67
Cercidiphyllum	6	901	150.17
Juniperus	3	444	148
Magnolia	94	13908	147.96
Lagerstroemia	93	13724	147.57
Platanus	45	6588	146.4
Ilex	47	6639	141.26
Tilia	13	1681	129.31
Fagus	5	642	128.4
Liquidambar	15	1861	124.07
Gymnocladus	2	247	123.5
Prunus	77	9317	121
Taxodium	13	1562	120.15
Amelancier	64	7372	115.19
Ulmus	316	35640	113.14
Parrotia	3	337	112.33
Pinus	5	558	111.6
Koelreuteria	9	989	109.89
Celtis	7	723	103.29
Cercis	130	13371	102.85
Cedrus	6	617	102.83
Carpinus	19	1857	97.74
Malus	6	538	89.67
Cyptomeria	1	83	83
Gleditsia	17	1393	81.94
Cornus	44	3453	78.48
Ostrya	17	1263	74.29
Nyssa	36	2367	65.75

Ginkgo	15	966	64.4
Chionanthus	41	2619	63.88
Diospyros	3	153	51
Syringa	5	253	50.6
Pistacia	3	137	45.67
Helesia	1	41	41

Appendix 6: Tree Plantings by Condition Category

The tables below (6.1, 6.2, 6.3, 6.4) show the number and percentage of trees sampled within each condition category (i.e., dead, good, poor) by genus for trees planted in Washington, D.C. in 2005, 2006, 2007 and 2008. The last table (6.5) shows all of these years combined. Finally, each of these tables is sorted from genera with the highest to lowest percentage of trees in the dead+poor condition category.

6.1: 2005

Genus	# of Good	# of Poor	# of Dead	Total	% D+P	% Good
Hamamelis	0	0	3	3	100	0
Stewardia	0	0	1	1	100	0
Aronia	1	0	5	6	83	17
Nyssa	1	0	5	6	83	17
Pinus	6	0	14	20	70	30
Liquidambar	6	0	12	18	67	33
Syringa	2	0	4	6	67	33
Cornus	16	0	31	47	66	34
Taxodium	3	0	5	8	63	38
Magnolia	23	2	28	53	57	43
Juniperus	13	2	13	28	54	46
Metasequoia	2	0	2	4	50	50
Carpinus	4	0	4	8	50	50
Fagus	2	0	2	4	50	50
Tilia	6	2	4	12	50	50
Ilex	13	1	9	23	44	56
Gleditsia	5	2	2	9	44	55
Quercus	77	1	52	130	41	59
Cercis	23	0	12	35	34	66
Cedrus	2	0	1	3	33	67
Acer	49	0	22	71	31	69
Amelanchier	31	1	12	44	30	70
Betula	16	0	7	23	30	70
Lagerstroemia	48	0	18	66	27	73
Liriodendron	17	0	6	23	26	74
Plantanus	36	2	9	47	23	77
Chionanthus	14	1	3	18	22	78
Prunus	61	4	8	73	16	84
Ulmus	113	4	15	132	14	86
Ginko	9	0	1	10	10	90

n=931

6.2: 2006

Genus	# of Good	# of Poor	# of Dead	Total	% D+P	% Good
Cedrus	0	0	2	2	100	0
Halesia	0	1	3	4	100	0
Parrotia	0	0	2	2	100	0
Pinus	0	0	2	2	100	0
Juniperus	1	0	15	16	94	6
Ginkgo	1	0	3	4	75	25
Taxodium	4	0	10	14	71	29
Plantanus	19	3	42	64	70	30
Betula	13	1	26	40	68	33
Quercus	44	2	64	110	60	40
Hamamelis	10	2	9	21	52	48
Syringa	3	1	2	6	50	50
Gleditsia	7	5	1	13	46	54
Cornus	27	2	14	43	37	63
Magnolia	34	6	13	53	36	64
Acer	30	4	11	45	33	67
Tilia	2	0	1	3	33	67
Prunus	37	1	17	55	30	70
Amelanchier	42	1	16	59	29	71
Ulmus	125	5	40	170	26	74
Fagus	3	1	0	4	25	75
Liriodendron	3	0	1	4	25	75
Cercis	56	5	13	74	24	76
Carpinus	18	3	2	23	22	78
Lagerstroemia	59	0	16	75	21	79
Ilex	22	1	4	27	19	81
Liquidambar	5	0	1	6	17	83
Chionanthus	7	0	1	8	13	88
Cladrastis	8	1	0	9	11	89
Gymnocladus	2	0	0	2	0	100
Malus	3	0	0	3	0	100
Nyssa	1	0	0	1	0	100
Picea	1	0	0	1	0	100
Styrax	1	0	0	1	0	100

n=964

6.3: 2007

Genus	# of Good	# of Poor	# of Dead	Total	% D+P	% Good
Picea	3	0	7	10	70	30
Cercidiphyllum	4	0	9	13	69	31
Malus	1	0	2	3	67	33
Liriodendron	1	0	1	2	50	50
Nyssa	35	1	23	59	41	59
Quercus	29	2	18	49	41	59
Cornus	6	1	3	10	40	60

Cotinus	3	0	2	5	40	60
Liquidambar	9	1	4	14	36	64
Aesculus	2	0	1	3	33	67
Ostrya	2	1	0	3	33	67
Platanus	18	0	9	27	33	67
Amelanchier	21	0	10	31	32	68
Cladrastis	5	0	2	7	29	71
Chionanthus	31	2	10	43	28	72
Lagerstroemia	27	1	9	37	27	73
Magnolia	43	2	14	59	27	73
Betula	57	3	16	76	25	75
Prunus	30	0	9	39	23	77
Acer	11	0	3	14	21	79
Ulmus	177	1	43	221	20	80
Ginko	13	0	3	16	19	81
Ilex	21	4	1	26	19	81
Cercis	66	3	11	80	18	83
Cedrus	5	0	1	6	17	83
Gladitsia	5	1	0	6	17	83
Koelreuteria	7	1	0	8	13	88
Taxodium	7	0	1	8	13	88
Tilia	10	1	0	11	9	91
Carpinus	13	0	0	13	0	100
Celtis	7	0	0	7	0	100
Cryptomeria	1	0	0	1	0	100
Diospyros	3	0	0	3	0	100
Fagus	1	0	0	1	0	100
Juniperus	1	0	0	1	0	100
Metasequoia	5	0	0	5	0	100
Parrotia	2	0	0	2	0	100
Pinus	5	0	0	5	0	100
Pistacia	1	0	0	1	0	100
Styrax	1	0	0	1	0	100

n=926

6.4: 2008

Genus	# of Good	# of Poor	# of Dead	Total	% D+P	% Good
Ficus	0	0	1	1	100	0
Populus	0	1	2	3	100	0
Liriodendron	1	0	6	7	86	14
Hamamelis	1	0	5	6	83	17
Carya	1	0	3	4	75	25
Cupressus	1	0	2	3	67	33
Nyssa	69	2	76	147	53	47
Cornus	11	0	12	23	52	48
Cotinus	1	0	1	2	50	50
Diospyros	1	0	1	2	50	50

Ginkgo	5	2	3	10	50	50
Gleditsia	2	0	2	4	50	50
Picea	1	0	1	2	50	50
Salix	1	0	1	2	50	50
Taxodium	5	0	3	8	38	63
Betula	91	3	49	143	36	64
Fagus	11	0	4	15	27	73
Ostrya	6	0	2	8	25	75
Acer	33	0	9	42	21	79
Juniperus	8	0	2	10	20	80
Pinus	4	0	1	5	20	80
Thuja	4	0	1	5	20	80
Magolia	54	2	11	67	19	81
Quercus	78	1	16	95	18	82
Tilia	10	0	2	12	17	83
Cercis	64	1	11	76	16	84
Liquidambar	16	0	3	19	16	84
Ulmus	256	3	43	302	15	85
Chionanthus	12	1	1	14	14	86
Prunus	34	0	5	39	13	87
Amelanchier	33	1	3	37	11	89
Carpinus	8	0	1	9	11	89
Cryptomeria	9	0	1	10	10	90
Ilex	25	1	1	27	7	93
Platanus	15	1	0	16	6	94
Cladrastis	19	0	1	20	5	95
Asimina	1	0	0	1	0	100
Cedrus	8	0	0	8	0	100
Celtis	6	0	0	6	0	100
Cercidiphyllum	5	0	0	5	0	100
Koelreuteria	2	0	0	2	0	100
Lagerstroemia	3	0	0	3	0	100
Malus	1	0	0	1	0	100
Metasequoia	2	0	0	2	0	100
Oxydendrum	1	0	0	1	0	100
Pyrus	2	0	0	2	0	100
Styrax	2	0	0	2	0	100
Zelkova	3	0	0	3	0	100

n=1,231

6.5: Combined (2005-2008)

Genus	# of Good	# of Poor	# of Dead	Total	% D+P	% Good
Ficus	0	0	1	1	100	0
Halesia	0	1	3	4	100	0
Populus	0	1	2	3	100	0
Stewardia	0	0	1	1	100	0
Aronia	1	0	5	6	83	17

Carya	1	0	3	4	75	25
Cupressus	1	0	2	3	67	33
Hamamelis	11	2	17	30	63	37
Picea	5	0	8	13	62	38
Juniperus	23	2	30	55	58	42
Syringa	5	1	6	12	58	42
Pinus	15	0	17	32	53	47
Cornus	60	3	60	123	51	49
Cercidiphyllum	9	0	9	18	50	50
Parrotia	2	0	2	4	50	50
Salix	1	0	1	2	50	50
Taxodium	19	0	19	38	50	50
Viburnum	1	0	1	2	50	50
Nyssa	106	3	104	213	50	50
Cotinus	4	0	3	7	43	57
Platanus	88	6	60	154	43	57
Gleditsia	19	8	5	32	41	59
Quercus	228	6	150	384	41	59
Liriodendron	22	0	14	36	39	61
Liquidambar	36	1	20	57	37	63
Betula	177	7	98	282	37	63
Magnolia	154	12	66	232	34	66
Aesculus	2	0	1	3	33	67
Ginkgo	28	2	10	40	30	70
Malus	5	0	2	7	29	71
Fagus	17	1	6	24	29	71
Acer	123	4	45	172	28	72
Ostrya	8	1	2	11	27	73
Amelanchier	127	3	41	171	26	74
Tilia	28	3	7	38	26	74
Lagerstroemia	137	1	43	181	24	76
Chionanthus	64	4	15	83	23	77
Cedrus	15	0	4	19	21	79
Cercis	209	9	47	265	21	79
Ilex	81	7	15	103	21	79
Prunus	162	5	39	206	21	79
Diospyros	4	0	1	5	20	80
Thuja	4	0	1	5	20	80
Ulmus	670	13	140	823	19	81
Carpinus	43	3	7	53	19	81
Metasequoia	9	0	2	11	18	82
Cladrastis	32	1	3	36	11	89
Koelreuteria	9	1	0	10	10	90
Cryptomeria	10	0	1	11	9	91
Asimina	1	0	0	1	0	100
Celtis	13	0	0	13	0	100
Gymnocladus	2	0	0	2	0	100

Oxydendrum	1	0	0	1	0	100
Pistacia	1	0	0	1	0	100
Pyrus	2	0	0	2	0	100
Styrax	4	0	0	4	0	100
Zelkova	3	0	0	3	0	100

N=4,052

Appendix 7: Results of the factor-level chi-square tests for the pre-planting, environmental and socioeconomic variables

The tables below show the frequency and percentage of trees within each of the factor's (i.e., nursery, stock type, planting season, planting year, landuse and space type) levels by condition category (i.e., good and dead+poor) for trees observed in Washington, D.C. in summers 2008, 2009, 2010 and 2011. The right side of table shows the corresponding p-values for each factor-level chi-square tests. Each table is sorted from high to low percentage of dead+poor trees.

7.1: Nursery

Freq. %	Good	D + P	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12
N1	107	170	---											
	39%	61%												
N2	42	61	0.7924	---										
	40%	59%												
N3	47	69	0.8129	1	---									
	41%	59%												
N4	242	181	<0.0001*	0.0038*	0.002*	---								
	57%	43%												
N5	250	137	<0.0001*	<0.0001*	0.0001*	0.0376*	---							
	65%	35%												
N6	105	54	<0.0001*	<0.0001*	<0.0001*	0.0659	0.8248	---						
	66%	34%												
N7	151	69	<0.0001*	<0.0001*	<0.0001*	0.0062*	0.3573	0.673	---					
	69%	31%												
N8	14	6	0.0117*	0.0311*	0.0275*	0.3681	0.8001	0.9184	1	---				
	70%	30%												
N9	147	56	<0.0001*	<0.0001*	<0.0001*	0.0003*	0.0673	0.2325	0.4569	1	---			
	72%	28%												
N10	67	22	<0.0001*	<0.0001*	0.3065	0.0023*	0.0716	0.1704	0.3065	0.8374	0.7143	---		
	75%	25%												
N11	989	232	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.3406	0.0064*	0.2386	---	
	81%	19%												
N12	522	114	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.0015*	<0.0001*	0.2794	0.004*	0.1636	0.6153	---
	82%	18%												

N= 3,854 *Significant at alpha=0.05; Continuity adjusted p-values

7.2: Stock Type

Frequency Row percent	Good	Dead+Poor	CON	B&B
CON	737 68%	348 32%	---	
B&B	2059 70%	893 30%	0.2826	---

N= 4,037; B&B= Balled & burlapped; CON= Container grown
*Significant at alpha=0.05; Continuity adjusted p-values

7.3: Planting Season

Frequency Percent	Good	Dead+Poor	Summer	Spring	Fall	Winter
Summer	26 44%	33 56%	---			
Spring	1264 63%	755 37%	0.0058*	---		
Fall	1125 76%	362 24%	<0.0001*	<0.0001*	---	
Winter	388 79%	101 21%	<0.0001*	<0.0001*	0.1075	---

N= 4,054
*Significant at alpha=0.05; Continuity adjusted p-values

7.4: Planting Year

Frequency Percent	Good	Dead+Poor	2006	2005	2007	2008
2006	589 61%	377 39%	---			
2005	599 64%	332 36%	0.1422	---		
2007	689 74%	237 26%	<0.0001*	<0.0001*	---	
2008	926 75%	305 25%	N/A	N/A	N/A	---

N= 4,054
*Significant at alpha=0.05; Continuity adjusted p-values

7.5: Landuse

Freq. %	Good	P+D	PRO	RSD	MXL	FDR	LPF	CMM	INS
PRO	682	413	---						
	62%	38%							
RSD	1442	655	0.0003*	---					
	69%	31%							
MXL	114	37	0.0021*	0.1001	---				
	75%	25%							
FDR	26	8	0.1324	<0.0001*	1	---			
	76%	24%							
LPF	326	104	<0.0001*	0.0044*	1	1	---		
	76%	24%							
CMM	62	18	0.0092*	0.0971	0.8589	1	0.8557	---	
	78%	23%							
INS	150	14	<0.0001*	<0.0001*	0.0002*	0.0256*	<0.0001*	0.0046*	---
	91%	9%							

N= 4,051; CMM= Commercial; FDR= Federal; INS= Institutional; LPF= Local public facilities; MXL= Mixed landuse; PRO= Park, recreation and open space; RSD= Residential
*Significant at alpha level=0.05; Continuity adjusted p-values

7.6: Space Type

Frequency Percent	Good	Dead+Poor	TB	OL	CS
TB	564	307	---		
	65%	35%			
OL	1668	786	0.0901	---	
	68%	32%			
CS	571	151	<0.0001*	<0.0001*	---
	79%	21%			

N= 4,047
*Significant at alpha=0.05; Continuity adjusted p-values

7.7: Jurisdiction

Freq. %	Good	P+D	CMM	NPS	DPR	DCPS	PRV	RSD	DDOT	SCH
CMM	160	118	---							
	58%	42%								
NPS	204	147	0.951	---						
	58%	42%								
DPR	489	325	0.5041	0.5766	---					
	60%	40%								
DCPS	346	159	0.0028*	0.0023*	0.0024*	---				
	69%	31%								
PRV	698	278	<0.0001*	<0.0001*	<0.0001*	0.2541	---			
	72%	28%								
RSD	142	56	0.0014*	0.0014*	0.0032*	0.4606	1	---		
	72%	28%								
DDOT	652	129	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.0002*	---	
	83%	17%								
SCH	40	0	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.0002*	0.0003*	0.0100*	---
	100%	0%								

N= 3,943; CMM= Commercial; DCPS= D.C. Public Schools; DDOT= D.C. Department of Transportation; DPR= D.C. Department of Parks and Recreation; NPS= National Park Service; PRV= Private; SCH= School or university; RSD= Residential

*Significant at alpha=0.05; Continuity adjusted p-values

7.8: Genera

Freq %	Good	P+D	Nys	Que	Bet	Mag	Ace	Ame	Lag	Pru	Cer	Ulm
Nys	106	107	---									
	50%	50%										
Que	228	156	0.0293*	---								
	59%	41%										
Bet	177	105	0.0051*	0.4206	---							
	63%	37%										
Mag	154	78	0.0005*	0.099	0.448	---						
	66%	34%										
Ace	123	49	<0.0001*	0.0081*	0.0707	0.322	---					
	72%	28%										
Ame	127	44	<0.0001*	0.001*	0.0154*	0.1109	0.6506	---				
	74%	26%										
Lag	137	44	<0.0001*	0.0002*	0.0051*	0.0513	0.4413	0.8535	---			
	76%	24%										
Pru	162	44	<0.0001*	<0.0001*	0.0003*	0.0060*	0.1382	0.3806	0.5691	---		
	79%	21%										
Cer	209	56	<0.0001*	<0.0001*	<0.0001*	0.0017*	0.1002	0.318	0.5	1	---	
	79%	21%										
Ulm	670	153	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.0046*	0.0428*	0.0988	0.4212	0.4101	---
	81%	19%										

n= 2,929; Ame= Amelanchier; Ace= Acer; Lag= Lagerstroemia; Pru= Prunus; Nys= Nyssa; Mag= Magnolia; Cer= Cercis; Bet= Betula; Que= Quercus; Ulm= Ulmus
*Significant at alpha=0.05; Continuity adjusted p-values

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