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THE INFLUENCE OF INITIAL TREE SIZE ON GROWTH,
CANOPY DEVELOPMENT, AND PHYSIOLOGY IN THE
URBAN ENVIRONMENT

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THE INFLUENCE OF INITIAL TREE SIZE ON GROWTH, CANOPY DEVELOPMENT, AND PHYSIOLOGY IN THE URBAN ENVIRONMENT

By

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ABSTRACT

THE INFLUENCE OF TREE STOCK SIZE ON GROWTH, CANOPY DEVELOPMENT, AND TREE PHYSIOLOGY IN THE URBAN ENVIORNMENT

By:

Matthew Paul Ross

Proper selection of tree size is essential to maximize the efficiency of canopy restoration efforts. Municipal and landscape ordinances often specify the use of large caliper trees, 7.6 cm (2.5 in) or larger, to provide a more substantial impact. However, the costs associated with transplanting larger caliper trees can have a negative impact on planting budgets resulting in fewer trees planted on a site. In this project three hundred trees of five different stock sizes 4.4 cm (1.75 in), 5.1 cm (2 in), 6.4 cm (2.5 in), and 7.6 cm (3 in) balled-and-burlapped, and 4.4 cm (1.75 in) bare-root stock were planted in four Michigan communities. Our objectives were to: 1) Quantify the influence of stock size on growth, canopy development, and physiological function during establishment 2) Characterize the relationship between soil and environmental factors on growth and tree physiology in the urban environment 3) Provide recommendations to municipal arborist to increase the efficiency of canopy restoration programs through proper size selection. Our study quantified the differences in growth, canopy development, and physiology of Autumn Blaze maple (*Acer* x *freemanii* 'Autumn Blaze'), swamp white oak (*Quercus bicolor*), and Bloodgood London plane tree (*Platanus* x *acerfolia* 'Bloodgood'). During the first two years of establishment, significant differences in the rate of canopy development, trunk growth, and shoot elongation suggest that smaller trees establish at a faster rate than large trees in the urban environment. However, the relationship between stock size and gas exchange was not significant.

-Dedicated to my late grandfather, Harold M. White, who taught me the valor in good, honest hard-work

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TREES, PEOPLE, RESTORATION, AND THE URBAN FOREST

The Urban Forest

The urban forest is defined in the National Assessment of Our Urban Forest as "…an ecosystem characterized by the presence of trees and other vegetation in association with people and their developments." (Dwyer et al. 2000). This includes all trees growing in cities and suburban areas with a population density greater than 384 people per square kilometer surrounding a population center of over 50,000 residents (Dwyer et al., 2000). Current estimates of the national urban forest population conducted by the United States Department of Agriculture Forest Service are 3.8 billion trees (Dwyer et al. 2000 and Nowak et al. 2001). This resource is increasingly important due to its economic and environmental impact. Although urban forests are a highly valued resource providing mediation between the built-environment and the surrounding ecosystem; it remains relatively understudied (Oke, 1989 and Pauliet and Duhme, 2000).

Humans in metropolitan and urban areas are increasingly dependent upon urban trees for their social, economic, and environmental benefits (Roberts, 1977). An estimated 80% of the population of the United States, directly benefit from urban forests on a daily basis (Dwyer et al., 1999 and Dwyer et al., 2003). Recent efforts to quantify these benefits (Dwyer et al., 1992; Dwyer and Miller, 1999; McPherson et al., 1999; and Nowak et al., 2002) have led to increased public awareness of the multitude of benefits it provides. Furthermore, increased interest in sustainable forest management has solidified a link between the urban forest and society (Van Herzele et al., 2005).

Sociological and psychological benefits from tree planting, preservation, and maintenance are essential components adding to the complexion of a community.

Property value, commercial success, and affluence have been correlated with canopy cover. In addition, urban forests act as a buffer to mediate the deleterious effects of human development on the environment. Without trees the negative impact of the built-environment on the surrounding ecosystems are exacerbated, property values diminish, and the social benefits of a community are compromised.

Micro-climates formed by tree canopies have been found to moderate surrounding temperatures (Oke et al., 1989). Energy costs for heating and cooling of nearby structures can be reduced through shading, light interception, slower localized windspeeds, and the release of water vapor during transpiration (Oke et al., 1989; McPherson, 1994). An analysis of Chicago's urban forest concluded that 70% of the total energy savings from trees are associated with the shade and reduction in windspeed associated with mature trees (McPherson, 1994). Annual energy savings of \$36 per tree were formulated for Chicago residents in 1994 (McPherson, 1994) and an average of 30% reduction in cooling costs in Sacramento, California in 1992 during peak consumption (Akbari et al., 1997). Geographic location, species, age of trees, and proximity to buildings are factors which influence the energy savings provided by trees.

Martin et al. (1989) found that residential property values are directly related to canopy cover. Their study evaluated the influence of canopy coverage on residential property values in Dallas, Texas and concluded that trees represent approximately 13% of the selling price of a home. Further research indicated that neighborhoods that had land under canopy cover were correlated with higher mean household incomes (Iverson and Cook, 2000 and Heynen and Lindsey, 2003). In addition to increased property value, established trees increase the rental rate of commercial office buildings (Laverne and

Winson-Geidman, 2003). The aesthetic value and provided shade to the buildings is attributed with a 7% increase in rental rates.

Trees can also aid in reducing atmospheric pollution. Research conducted by the United States Forest Service concluded that trees can reduce the amount of ozone, nitrous oxide, carbon monoxide, and other pollutants (Nowak et al., 2002) in urban areas. There is increasing interest in the levels of carbon sequestered by the urban forest and its relative importance in mitigating the possible effects of global climate change (Ip, 1996; Brack, 2002 ;and Nowak et al, 2002;). An estimated 700 million tons of carbon are currently stored in the national urban forest (Dwyer et al., 1999). Furthermore, the urban forests are responsible for annually sequestering 22.8 tons of carbon (Nowak and Crane, 2002b).

The urban heat island effect is considered the most researched anthropogenic climate modification over the last thirty years (Arnfield, 2003). Quantifying the ability of trees to mediate temperatures in urban environments was the central focus of the Chicago Urban Forest Climate Project (CUFCP) which began in 1990 (McPherson et al.,1997). Multi-disciplinary research characterized the role of trees in ameliorating effects of increased temperatures associated with the built-environment. Conclusions suggest that green spaces associated with building sites can reduce ambient air temperatures by as much as 3°C (McPherson et al., 1997).

In addition to reducing temperature and improving air quality, trees provide hydrologic benefits. The initiation of EPA regulations on water runoff further increased interest in hydrologic benefits provided by urban canopy cover. During rainfall events, leaves intercept precipitation reducing the intensity and volume of discharge (Dwyer et al., 1992).

Trees provide the social framework for a municipality to have a "sense of community" with the psychological benefits of a connection between humans and nature (Ames, 1980 and Dwyer et al. 1991). An overview of different urban planting initiatives in Sacramento, California linked group planting projects with positive social interactions (Sommer et al., 1994). Furthermore, Dwyer et al. (1991) found that personal connections with nature had spiritual, emotional, and philosophical importance. Social and psychological benefits of tree planting are often intangible (Van Herzele et al., 2005), but are considered essential for community involvement in urban tree programs (Sklar and Ames, 1985).

In addition to the social importance described by a multitude of researchers; trees play an integral role in cultures around the world. Festivals are scheduled based on tree phenology, economically important tree crops are essential components in determining land use, and some trees have a spiritual or religious connection to their community. Cristancho and Vining (2004) described species which are highly valued for their importance to the culture within their eco-region as "cultural keystone species." The importance of cultural keystone species provides a substantial contribution to their conservation and their incorporation in restoration efforts (Joseph and Mansourian, 2005). Furthermore, incorporating cultural principles in restoration efforts goes beyond the biological needs of the ecosystem.

Benefits provided by urban canopies extended beyond the realm of humans to include wildlife habitat. Urbanization resulting in changes in land use patterns, often results in large-scale alteration of previously undeveloped land. Subsequent removal or fragmentation of ecosystems, result in a decreased abundance of native flora and fauna (Collinge, 1996 and Zipperer et al., 1997). Even vegetative corridors which are thought to limit the severity of habitat loss, may have limited success providing a connection to a more suitable habitat (Collinge, 1996). Therefore, the urban forests are a vital resource for displaced animal-life and provide the framework for restoration of the ecosystem affected by urbanization. The function and contribution of the re-vegetated environment are dependent upon management strategies which can influence the ability to provide essential elements for species survival (Zipperer et al., 1997).

A multitude of stakeholders and partners are involved in the planning, planting, and maintenance of urban forests. Stakeholders are individuals and organizations which receive direct benefit from the urban forest, without physically contributing to the process (Brown, 2005 and Jones et al., 2005). Partners are individuals and organizations which are directly involved in the installation and management of the forest resource. Without cooperative participation of stakeholders and partners, management of urban forests can fail and planting efforts can be compromised. It is imperative for urban foresters to extend their management skills to incorporate personal and financial management of the resources contributed by stakeholders and partners involved in the urban forest (Jones et al., 2005).

It is essential for urban foresters to involve the community when planning, installing, and maintaining trees. Management of the many individuals, organizations, and institutions involved in urban forestry is one of the most challenging and vital roles of the urban forester (Dwyer and Schroeder, 1994). Conclusions from a survey conducted by Sommer et al. (1994), found that trees that were planted with help from community members were valued more than those planted by municipal foresters. In addition, forest managers were more likely to receive information about maintenance and condition of trees planted in association with community members (Sommer et al., 1994). Research in Oakland, California observed a 60-70% increase in survival of street trees which included community participation. Sklar and Ames (1985) found that programs which did not incorporate community involvement in the planning and planting of trees were failures due to vandalism with close to 100% mortality after six years. Direct community involvement is essential to the success of maintaining, preserving, and restoring the urban forest for future generations.

Tree Growth and Development in the Urban Environment

Sup-optimal growth conditions (Berrang, 1985; Oke et al., 1989; and Iles, 2003), high mortality, and limited life spans of urban trees (Foster and Blaine, 1978) all pose a threat to continued health of urban forests. A study evaluating Boston's urban forest concluded that the life span of an urban tree is limited to as few as ten years (Foster and Blaine, 1978). Trees in urban environments are subjected to additional stresses when compared to trees grown in natural forest ecosystems, which limits their growth and development potential (Roberts, 1977; Kozlowski, 1985; Lauderdale et al., 1995; and Close et al., 1996). In addition to similar abiotic and biotic pressures present in their native environment, stress in the urban landscape increase precipitously with human development (Bassuk and Whitlow, 1986). Anthropogenic stress, such as vandalism, not normally associated with the natural environment can result in high mortality rates (Ames, 1985). Added pressure from exotic pests and pathogens further threaten the tability of the urban forest. Devastation caused by the emerald ash borer in the Midwestern United States is a testament to the vulnerability of this resource.

A multitude of soil (Craul, 1985; Jim, 1998; and DeKimpe et al., 2000) atmospheric (Whitlow and Bassuk, 1988; Cregg and Dix, 2001), and environmental (Kozlowski, 1987 and Oke et al., 1989) causes have been correlated with limited plant growth in the urban environment (Roberts, 1977; Clark and Kjelgren, 1990; Whitlow et al., 1992; and Close, 1996). High soil bulk density and degraded soil structure, as a result of compaction, limit soil water availability for urban trees (Jim, 1998 and DeKimpe et al., 2000). In addition to reduced infiltration from soil compaction, atmospheric drought can result in decreased plant water potential (Kozlowski, 1987 and Whitlow et al., 1992) and subsequently suppressed growth. Atmospheric deficits also increase transpiration water loss, reduce the rate of water absorption by the root system, and reduce net photosynthesis.

Adverse soil conditions are detrimental to plant health, vigor, and can lead to premature death. In the urban environment, up to 80% of tree problems are correlated with poor soil conditions (Patterson, 1980). Soils in urban planting areas are usually composed of composite materials with little or no organic material, a heterogeneous texture, and poor structure (Craul, 1992; Jim, 1998; and Dekimpe et. al, 2000). Despite global research efforts, there still remains a need to further quantify and qualify the properties of urban soil and their effect on plant physiology (Dekimpe et. al, 2000).

Soil compaction is inherent in urban environments where heavy foot traffic, human development, and the use of heavy equipment are ubiquitous. Furthermore, compacted sub-soils required in site construction decrease the space available for root growth of nearby trees. Soil compaction dramatically alters soil structure and results in increased bulk density, reduced porosity, decreased permeability, and disrupted soil aggregation (Hillel et al., 1980; Kozlowski, 1999).

Quantifying of bulk density within urban environments is increasingly important for soil scientists, urban planners, and municipal arborists (Dekimpe et al., 2000). Previous research has suggested a bulk density of 1.6 g/ cm^3 as the maximum threshold where root growth is unaffected (Foil and Ralston, 1967, Heilman, 1981; Landon, 1991). However, soil composition highly influences the threshold at which plant growth is limited (Zisa, 1980). A reduction in the rate of root expansion was evident at bulk densities as low as 1.4 g/ cm^3 and 1.8 g/ cm^3 for clay and sandy soils respectively (Zisa, 1980). In a survey of urban soils, Jim (1998) observed bulk densities as high as 2.63 g/cm^3 along roadsides in Hong Kong. Various remediation methods have been suggested by Day et al. (1995), however preventing soil compaction is the most effective management strategy to promote healthy plantings (Kozlowski, 1999).

Reduced porosity as a function of soil compaction is one of the leading causes of water stress in urban environments (Bassuk et. al, 2001). A reduction in micro-porosity associated with soil compaction reduces the water holding capacity of soil (Zisa, 1980). In addition, soil compaction affects water flow through the soil profile by reducing the connectivity of macro-pores which are the driving force for hydraulic flow (Hillel et al., 1980). Based on rainfall, there is an inverse relationship between soil compaction and porosity resulting in periods of water logging and extreme drought. This relationship is further exacerbated by increases in impermeable surfaces from human development. Berrang et al. (1985) observed widespread water logging leading to decreased tree growth and death in New York City as a result of limited infiltration and runoff filled planting pits.

In addition to soil compaction, trees planted in the urban environment typically have limited rooting area restricted by impervious surfaces (Cregg, 1995). Trees are often planted along roadsides and in planters where infiltration is limited. The necessity for proper soil volume is directly related to the amount of surface area of the roots in relation to that of the planting soil (Kozlowski, 1987; Clark and Kjelgren, 1990; and Whitlow et al., 1992).

Metabolism of essential reactions in root development is influenced by soil temperatures. Maximum root growth of trees occurs at temperatures between 17-25° C (63-77° F). Although temperatures between 50-60° C (122-140° F) are lethal for roots, soil temperatures approaching this threshold limit their function and subsequently reduce root growth and water uptake.

Roberts (1977) described chemical stress as the most unique factor associated with the tree growth in the urban environment. Insecticides, pesticides, herbicides, fungicides, and growth regulators used for managing the landscape can have significant effects on plant physiology. Furthermore, deicing salt used in temperate climates affect soil pH and can lead to desiccation of plant material.

Water composes the majority of the fresh weight of trees, is essential for proper physiological function, and acts as a solvent for gas and mineral exchange to maintain turgor. Kramer (1987) attributed the role of water stress in tree growth to a water imbalance between deposits from irrigation and rainfall and withdrawals caused by soil evaporation and transpiration from the canopy. The balance between water deposits and withdrawals is responsible for delayed growth. Furthermore, alterations in transpiration during periods of low water potentials are species dependent (Kozlowski and Davies, 1975). Therefore, it is necessary to evaluate several species to validate the effect of water stress for a given ecosystem. Trees experiencing water stress are more susceptible to pest infestation (Cregg and Dix, 2001), decreased shoot growth (Close et al., 1996), and reduced photosynthetic production (Lauderdale et al., 1995).

Indicators of water stress include an overall reduction of tree size, trunk growth, and individual leaf area. Over 30 years ago, Kozlowski and Davies (1975) postulated that stomatal closure is the primary factor reducing transpiration in trees experiencing water stress and suggested that rapid stomatal closure following exposure to increased light intensity minimizes water loss. Prolonged water stress, referred to as drought stress, has varying effects on plant growth and development. The primary effects inhibition of photosynthesis, loss of turgor pressure, and reduction of metabolism of carbohydrates and nitrogen. Secondary symptoms include a reduction in cell size, and increased stomatal closure.

Pre-dawn plant moisture potential has also been directly correlated to differences in soil moisture content (Kozlowski, 1982 and Whitlow et al., 1992). A three year study of street trees in New York City (Whitlow et al., 1992) suggested that seasonal changes in pre-dawn plant moisture content was directly attributed to similar changes in soil moisture content, while trends of midday plant moisture potential were a function of atmospheric demand. Results further indicated that cumulative water deficits are prevalent in the Northeastern United States.

Status of Michigan's Urban Forest

The urban forest of Michigan includes a total of 111 million trees (Dwyer and Nowak, 1999) and is considered the epicenter of the emerald ash borer infestation. Emerald ash borer (*Agrilus planipennis*), is a phloem boring insect (Haack et al., 2002) that is responsible for the death of over 30 million ash (*Fraxinus* sp.) trees in the Midwestern United States and Ontario (http://www.emeraldashborer.info/). Originally identified in 2002 (Haack et al., 2002), the insect has dramatically altered the species composition, leaving much of the regional urban forest depleted. Its ability to rapidly spread is caused by a combination of the abundance of host plants and an ecosystem integrated within the supply routes of international trade (Poland and McCullough, 2006) and the distribution of firewood outside of the quarantine by residents within the quarantine. Heavily planted due to its stress tolerance and fast growth, *Fraxinus* is a key genera in the urban forest across a majority of North America. Wide-spread loss caused by the emerald ash borer infestation represents a significant threat to the ecological health and economic stability of affected communities.

Estimated replacement cost of Michigan's urban forest is over 71 billion dollars (Dwyer et al., 2000). As of 2004, Michigan has appropriated over 1 million dollars to replace over 10,000 dead ash trees (Poland and McCullough, 2006). However, this represents a small percentage of the trees which have been killed by the emerald ash borer. Future replacement programs will need to maximize their efficiency to properly restore the depleted canopy. In addition to increasing species diversity to avoid future epidemics (Bassuk, 1990; Santamour, 1990; and Poland and McCullough, 2006) it is essential to provide scientific evidence on replacement species for inclusion in tree restoration programs, in order to efficiently address the need to replant the canopy lost from the emerald ash borer infestation.

Urban Forest Restoration

Forests are vital to the success of mankind, especially the 60 million people that are directly dependent on forest resources (Dudley et al., 2005). Conserving, maintaining, and restoring urban forests is an expensive and intensive process for municipal foresters. Increasing the number of trees in stable forest communities is offset by parallel losses in other regions due to human development (Dudley et al., 2005). The rate of urbanization continues to rise (McDonnell et al., 1997 and Cohen, 2003) and subsequent removal of native forest ecosystems correlated with urban sprawl remains a threat to our natural environment (McDonnell and Picket, 1990). In order to retain the benefits of our forest community, restoration efforts are locally and globally important. Forest restoration must incorporate ecosystem and landscape orientated goals (Mansourian et al., 2005).

Ecological restoration is a multi-faceted approach that incorporates needs of human stakeholders, inhabitants of the ecosystem, and needs of the environment. Restoration in forestry has taken these needs into strategic planning by recreating habitat and natural processes disrupted by canopy loss. A set of ecologically derived criteria based on previous land cover and the needs of the ecosystem was provided by Keddy and Drummond (1996). Several species types ranging from trees to fungi must be accounted for in this process. Furthermore, ecological restoration requires a long period of time and proper planning for success.

In conjunction with ecological and culturally sensitive approaches to forest restoration aimed at preserving the historical and traditional values (Naveh, 2004), it is imperative to re-establish natural functions in the landscape (Dudley et al., 2005). The ability to restore a forest based on its function and utility embraces both the needs of conservation of our forest resource and land development. Understanding the function of forests prior to development can lead to more sensitive development with less impact on the forest resource. In addition, restoring the urban forest based on its function can increase the success of large-scale planting efforts.

The scope of restoration efforts are determined by proper planning, available funding, and the balancing of the needs of all stakeholders involved (Brown, 2005). Replacing the lost canopy as fast and effective as possible is essential to recover the numerous benefits that would be lost. Trees represent a significant investment in the community where they are planted. Initial cost of plants, planting, and subsequent maintenance require financial support for municipal forestry departments. An analysis of our urban forest estimates that each tree has a cost of $640 (Dwyer and Nowak, 1999).

Urban forestry departments are faced with the task of implementing proper management techniques to enhance establishment of newly planted trees, increase diversity of species selection, and select proper stock that can grow in sup-optimal conditions (Dwyer et al., 2003). Several researchers have characterized the success of urban tree planting programs (Table 1).

Relationships between stock size and post-transplant growth and development are of particular interest to urban foresters. The relative proximity of the urban forest to the built-environment increases the importance of analyzing trees in this dynamic environment. In addition, funding for maintenance and installation of urban trees is less than 1% of the total operating budget for the majority of municipalities in the United States (Bernhardt and Swiecki, 1993 and Tschantz and Sacamano, 1994). and declined (Galvin, 1999) as much as 40% between 1986 and 1994 (International Society of Arboriculture, 1995).

Limited funding provided for large-scale canopy restoration efforts exemplifies the need for proper size selection. Anecdotcal accounts provided by municipal arborists (Watson, 1985) and limited experimentation in the urban environment (Lauderdale et al., 1995) indicate that smaller trees establish faster and more successfully than larger trees. Litzow and Pellett (1982) stated a need for additional research to characterize difference between tree size and species establishment in urban environments in order to develop proper size recommendations. Costs and benefits of planting larger trees were reviewed by the Davey Tree Resources (Davey Resource Group, 2006) as a feasibility study for large-scale state plantings and the general sentiment of urban foresters was described as,

"Typically, urban tree managers prefer stock 2-3" in caliper for planting in their urban forest, primarily because of the instant tree presence and because vandalism tends to be reduced on larger caliper trees. But in a SIP (State Implementation Plan) planting, a budget adequate for large stock is unlikely"

One of the predominant factors that may limit the success of planting larger caliper trees in the urban environment is the longer duration of reduced growth associated with transplant shock. Although there is not a definitive, single cause of transplant shock (Watson, 1985), several factors are correlated with delayed or suppressed growth following transplanting of trees. Genetic variation (Reaves and Whitlow, 2004) , species interactions (Watson et al., 1986), cultural practices (Preaus and Whitcomb, 1980 and Ferrini et al., 2000), geographic location (Kjelgren and Clark, 1993; Cregg, 1995), site conditions (Krizek and Dubik, 1987; Vrecenak et al., 1989; Ferrini et al., 2000; and Cregg and Dix, 2001), time of year (Watson and Himelick, 1982) and stock size (Litzow and Pellett, 1983; Watson, 1985; Lauderdale, 1995; and Struve et al. 2000) have all been associated with the severity or duration of water stress trees experience directly after transplanting.

Post-transplant research correlating initial stock size with suppressed growth has primarily focused on the hypothesis presented by Watson (1985) that larger trees have a longer establishment period than smaller trees. A model was formulated based on theory that root to shoot ratios of larger caliper trees are less than that of smaller caliper trees. The ratio of the root system to the upper portion (crown/shoots) of the plant it provides with nutrients and water is referred to as the "root to shoot ratio". The model formulated by Watson (1985) suggests that smaller trees have the capacity to outgrow larger caliper trees when planted at the same time (Figure 1).

This theory is based upon previous conclusions that the roots of larger and smaller trees grow at relatively the same pace of roughly 45.7 cm (18 in) a year (Figure 2). As shown in Figure 1, a 25.4 cm (10 in) caliper tree may lose upwards of 95% of the root system when harvested (Watson and Himelick, 1982).Data used to formulate this model were collected while experimenting with small caliper 10 cm (4 in) and large caliper 25.4 cm (10 inch) trees (Watson, 1985). The root to shoot ratio theory is based on the comparison of the root system after harvesting to the corresponding shoots outlined by Watson and Himelick (1982).

Recent research focused on quantifying the influence of initial stock size on post-transplant growth has had conflicting results. Data collected by Watson (1985), Lauderdale (1995), and Gilman et al. (1998) supports the theory that smaller trees will surpass the growth of larger trees over time. Conversely, Struve et al. (2000) concluded that smaller trees may not outgrow larger trees when production method and genotype were controlled. A suggested difference in the rate of establishment between larger and smaller caliper trees is that the healthier more vigorous trees are harvested first and the remaining trees are left in production to be transplanted as large trees. This practice further confounds the difference in establishment of larger trees due to their pre-disposed inferiority (Struve et al., 2000). Differences in geographic location, high mortality rates, species selection, stock size selection, and water availability represent possible reasons for difference in analyzing establishment rates of different size trees.

Litzow and Pellett (1982) stressed the importance of correlating the conclusions of previous stock size studies with conditions in the urban environment. Urban conditions are responsible for as much as 86% variability of tree growth (Vrecenak et al., 1989) and have been directly correlated with limited growth (Cregg, 1995; Close et al., 1996; and Jim, 1998). Previous research characterizing the influence of stock size on post-transplant growth and development of trees has been limited to controlled conditions (Struve et al., 1995; Gilman et al., 1998).

There are a multitude of reasons for the variation of results of the studies conducted by Gilman et al. (1998), Lauderdale et al. (1995), Struve et al. (2002), Watson (1985), and Litzow and Pellett (1982). Each study focused on different species of trees, initial size classifications, cultural practices, sample sizes, and was subjected to different environmental conditions. High mortality rates of the large caliper oaks experienced a 58% loss the first year after transplanting (Struve et al., 2002) can confound results.

It is generally accepted that tree species have different growth rates. Therefore, results correlating tree size and post-transplant growth and development are species dependent. Previous studies have characterized the effect of size on *Acer platanoides* (Litzow and Pellett, 1982), *Acer rubrum* 'October Glory' (Lauerdale et al., 1995), *Quercus rubra* (Struve et al., 2002), *Quercus virginiana* (Gilman et al., 1998), *Fraxinus pennsylvanica* (Litzow and Pellett, 1982), and *Tilia cordata* 'Greenspire' (Litzow and Pellett, 1982). Species dependent trends were observed by Litzow and Pellett (1982) between the linden and maple trees when planted at the same location.

There is a greater difference between the trees used to create Watson's model (1985), 10.2 cm (4 in) and 25.4 cm (10 in) caliper than that of the other studies. Lauderdale et al. (1995) selected 3.8 cm (1.5 in) caliper trees as the criteria for small trees and 7.6 cm (3 in) caliper for the larger trees; Struve et al. (2002) compared 3.6 cm (1.4 in) and 8.4 cm (3.3 in) caliper trees, and Gilman et al. (1998) studied the differences between 6.4 cm (2.5 in) and 11.7 cm (4.6 in) trees. Litzow and Pellett (1982) evaluated several grades of bare-root stock from 0.91 m (3 ft) whips to 5.1 cm (2 in) caliper.

The influence of cultural practices on growth and development in the urban landscape has been the subject of research since the 1970's (Cool, 1976). Differences between bare-root and balled and burlapped transplant methods has had varying results. Advancements in transplant technology has led to the ability to successfully transplant just about any size tree and improved the practice of bare-root transplanting. Research evaluating the influence of stock sizes has incorporated a variety of production methods including bare-root branched and whips and transplants (Litzow and Pellett, 1982), balled and burlapped material (Litzow and Pellett, 1982; Lauderdale et al., 1995; Gilman et al. 1998)), containerized plants (Gilman et al., 1998; Struve et al., 2002), and tree-spaded material (Struve et al., 2002).

Limitations of sample size and differences between species limited the impact of the results found by Litzow and Pellett (1982). Trees larger than the 8'-branched grade showed a decreased rate of caliper development as size increased and larger sized linden transplants had a reduced success rate. Although the smaller grade trees may have established faster, they were also more susceptible to vandalism (Litzow and Pellett, 1982).

Gilman et al. (1998) found that after 27 months of growth, smaller live oaks (*Quercus virginia*) had a significantly greater increase of leader extension (p-value <0.01) and caliper development (p-value <0.01) than larger trees. The differences in primary and secondary growth rates indicated that when irrigated the smaller trees were establishing at a faster rate. At the end of the study, Gilman et al. (1998) observed similar dimensions of all remaining research trees, and suggested that Watson and Himelick's (1982) root to shoot ratio was responsible for the increased rate of establishment of smaller transplants.

Lauderdale et al. (1995) observed significant differences in growth and development of red maples (*Acer rubrum* 'October Glory') during the first two years of establishment. One years after transplanting, the only statistically differences in growth between the small and large transplants were recorded for shoot elongation 11.4 and 6.1 cm respectively. In addition to significant differences in shoot elongation, after two years height and caliper development were significantly greater for the small caliper transplants. Lauderdale et al. (1995) observed a significantly higher percentage of canopy depletion of larger trees. Only one of the smaller trees experienced a reduction in canopy while 37.5% of the initially larger trees experienced canopy loss greater than 25%.

Physiological evidence supporting the hypothesis that smaller trees establish at a faster rate than larger trees was also concluded by Lauderdale et al. (1995). Smaller trees had a significantly higher (p-value <0.05) photosynthetic rate, suggesting that they were under less stress. In addition, the smaller trees had higher stomatal conductance compared to larger trees throughout the experiment with values of .55, 2.18, and 2.31 cm/sec for August of 1993, June of 1994, and August of 1994 in comparison with .30, 1.59, and 1.67 cm/sec of the larger trees. Further evidence of the reduced stress of the smaller transplants was characterized by lower pre-dawn moisture potentials in August of 1993 and 1994.

Struve et al. (2002) attempted to limit possible confounding effects of provenance and variation in nursery production methods. The ratio of canopy volume to root mass was held constant to investigate differences in growth of different stock sizes. Oak trees were selected from an identical seed source in order control provenance. Production methods were controlled to prevent inferior stock from being left in production and later harvested as the larger trees. Furthermore, all trees were planted into proportionally accurate planting pits to investigate previous hypothesis suggested by Barnett et al. (1983) and Watson and Kupkowski (1991) that differences in growth of smaller and larger trees was attributed to disproportional planting pit volumes. During the study larger transplants experienced 58% mortality which severely limited the application of their results. Surviving larger caliper trees had greater trunk growth and height growth than the smaller trees after a four year period.

Watson (2005) reviewed the influence of tree size on transplant establishment and growth. He concluded that there was a definitive relationship between tree size and rate of establishment, however the hypothesis that the difference in recovery time will result in a smaller tree outgrowing a larger tree remained in question. A comparison of the trunk diameters from the research of Watson (1985), Lauderdale et al. (1995), and Gilman et al. (1998) during the first two years of establishment are presented in Figure 3. In addition, the need for long term research was suggested by Watson (2005).

Summary

Trees are a vital component to humans and their communities. Continued health and sustainability are essential to retain the economic, social, and environmental benefits from the urban forest resource. Currently in the Midwestern United States, the emerald ash borer infestation has re-iterated the importance of diversity within the urban landscape. Increasing urbanization, high mortality rates, sub-optimal soil conditions, poor atmospheric quality, and adverse human interaction present serious threats to urban forests. Efficient management decisions are essential to protect, maintain, and restore trees in the urban landscapes. Therefore, it is imperative for municipalities to maximize their return on investment for canopy restoration programs.

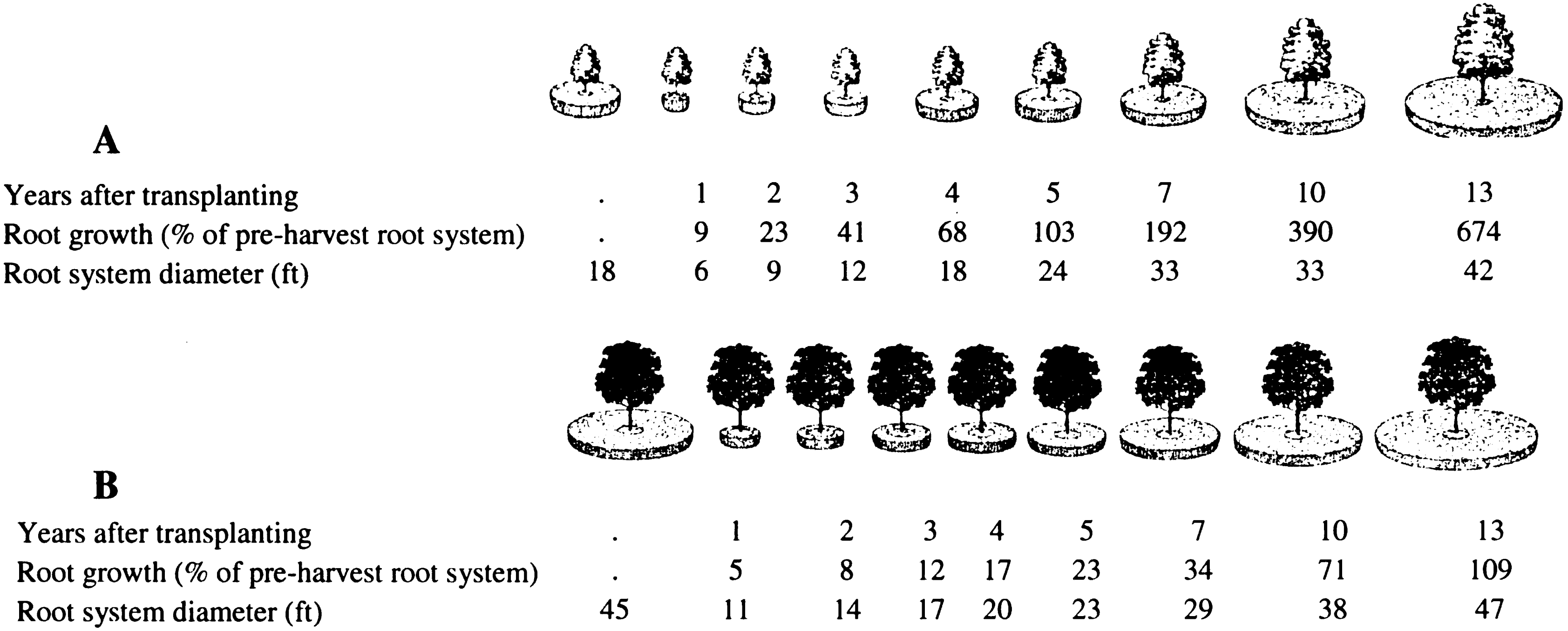
Since the inception of urban forestry, research has supported a need to advance our understanding of the effects of the built environment on tree growth and physiology. Alterations in the landscape are ubiquitous in urban environments and management strategies rely upon results of field research. Anecdotal claims of municipal arborists and previous work conducted in controlled experiments suggest that smaller trees establish better than larger trees. The loss of a key genus, ash (*Fraxinus* sp.), prompted a study to quantify the influence of initial stock size on growth and development of replacement species in the urban forest.

The following study was developed to characterize the growth response and canopy development of four different stock sizes while accounting for site and environmental conditions in the urban environment. The overall objective is to quantify the influence of initial tree size on establishment and subsequent development and provide recommendations to municipal arborists for increasing the efficiency of planting and canopy restoration programs.

Table 1. Studies evaluating annual mortality rates of establishing urban trees

Date	Researchers	Location	Duration	Annual Mortality Rate	Sample Size (Trees)
1985	Sklar and Ames	Oakland, California	6 years	7% and 20%	3500
1990	Gilbertson and Bradshaw	Liverpool, England	3 years	8%	401
1990	Nowak et al.	Oakland, California	2 years	19%	480
1991	Miller and Miller	Milwaukee and Waukesha, Wisconsin	4 years	6%	1,003
1996	Ip	Northwest Canada	3 years	7%	8.5 million
2001	White	Cleveland, Ohio	4 years	3%	7,969
2004	Nowak et al.	Baltimore, Maryland	2 years	9%	261
2004	Thompson et al.	Iowa	4 years	6%	932

Adapted from Davey Resource Group's state implementation plan: feasibility study Bond, 2006 and Roman, 2006



A

Years after transplanting	.	1	2	3	4	5	7	10	13
Root growth (% of pre-harvest root system)	.	9	23	41	68	103	192	390	674
Root system diameter (ft)	18	6	9	12	18	24	33	33	42

B

Years after transplanting	.	1	2	3	4	5	7	10	13
Root growth (% of pre-harvest root system)	.	5	8	12	17	23	34	71	109
Root system diameter (ft)	45	11	14	17	20	23	29	38	47

Figure 1. Relationship of root and canopy growth of 10.2 cm (4 in) (A) caliper and 25.4 cm (10 in) (B) trees for 13 years after transplanting adapted from Watson (1985) and revised by Watson (2005)

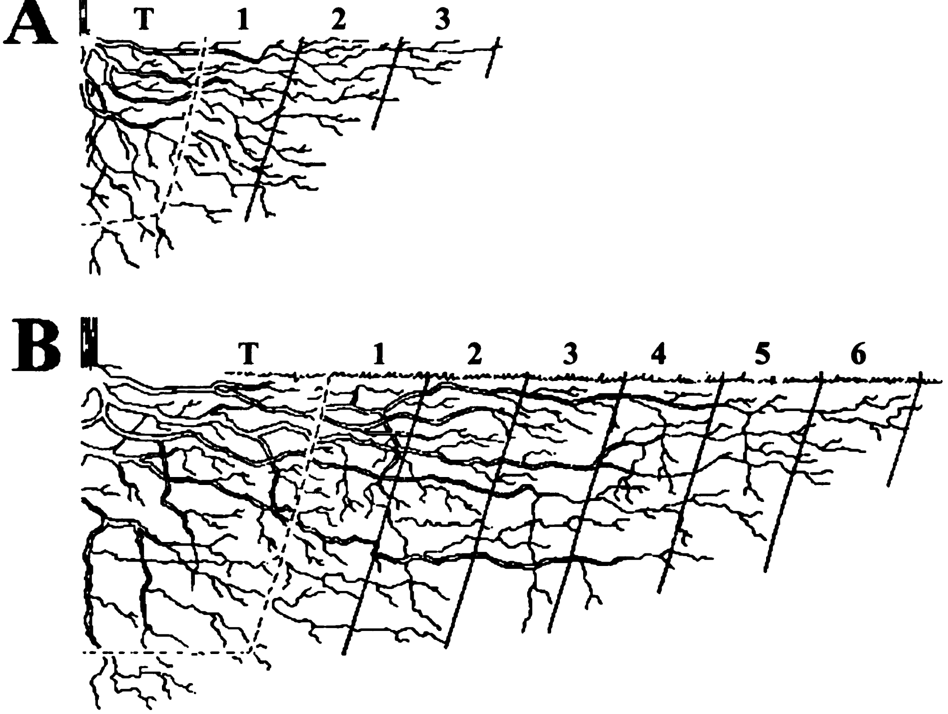


Figure 2. Diagram of root growth of initially smaller (A) and larger (B) trees a revision by Watson (2005) of the model by Watson and (1987)

Transplanting root mass (T) and three subsequent years for smaller tree and six years for the larger tree are represented numerically

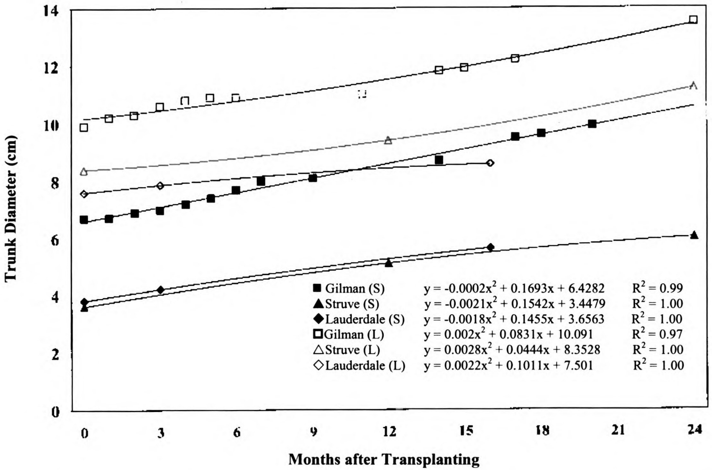


Figure 3. Polynomial regression of the trunk diameter (cm) during the first two years of establishment in large and small caliper studies by Lauderdale et al. (1995), Gilman et al. (1998), and Struve et al. (2000).

Taken from Watson (2005)

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CHAPTER ONE

THE INFLUENCE OF INTIAL STOCK SIZE ON TREE GROWTH AND CANOPY DEVELOPMENT IN THE URBAN ENVIRONMENT

THE INFLUENCE OF INTIAL STOCK SIZE ON TREE GROWTH AND CANOPY DEVELOPMENT IN THE URBAN ENVIRONMENT

Additional key words: Acer x *freemanii* 'Autumn Blaze', canopy volume, light interception, *Platanus* x *acerfolia* 'Bloodgood', *Quercus bicolor*, relative growth rate, restoration, shoot elongation, and urban soils.

Abstract

There is a need to quantify the influence of stock size on tree establishment to maximize efficiency of canopy restoration programs in the wake of the emerald ash borer infestation. Growth and canopy development of three ash replacement species; Autumn Blaze maple (*Acer* x *freemanii* 'Autumn Blaze') , Bloodgood London plane tree (*Platanus* x *acerfolia* 'Bloodgood'), and swamp white oak (*Quercus bicolor*) of five different size classifications; 4.4 cm (1.75 in) bare-root and balled-and-burlapped, 5.1 cm (2 in), 6.4 cm (2.5 in), and 7.6 cm (3 in) were recorded during the first two years after planting in four urban communities in Michigan. Canopy volume of maples, oaks, and 7.6 cm (3 in) plane trees declined during the first year. Although larger trees maintained significantly larger canopies two years after planting, the rate of canopy development, trunk growth, and shoot elongation suggest that smaller trees have a better establishment rate. Canopy dieback was prevalent in larger caliper trees, as a result their total impact on the planting site was reduced. Existing soil characteristics, in particular bulk density and pH, exhibited a stronger correlation on canopy development and trunk growth during the second year than the first year following transplanting.

Introduction

Large-scale canopy restoration efforts are essential following the wide-spread death of ash (*Fraxinus sp.)* trees caused by the emerald ash borer (*Agrilus planipennis*) infestation. A large portion of trees lost from the infestation were in urban locations (Poland and McCullough, 2006). The removal of over 30 million ash trees throughout all forests within the Midwestern United States (www.emeraldashborer.info) has placed an economic burden on several municipal, private, and public forest managers. Operating budgets for municipal forestry departments are increasingly limited (Galvin, 1999), therefore it is imperative for municipalities to maximize their return on investment for canopy restoration programs. The loss of a key genus, ash (*Fraxinus* sp.), prompted a study to quantify the influence of initial stock size on growth and development of replacement species in the urban forest. Current municipal landscape and woodland ordinances often have replacement specifications requiring minimum trees sizes of 6.35 cm (2.5 in) for woodland and 7.62 cm (3 in) calipers for landscape enhancement. These larger caliper trees provide a more substantial impact than smaller caliper trees immediately following planting, but represent a significant investment for municipal forestry departments due to the higher cost associated with their installation, maintenance, and potential replacement (Gilman et al., 1998). However, higher mortality rates (Struve et al., 2000), crown dieback (Lauderdale et al., 1995), and an extended period of delayed or suppressed growth (Watson, 1985) associated with transplant shock can adversely affect the impact provided by initially larger trees.

Larger trees experience greater transplant shock than smaller trees and the differences in their establishment rates (Watson, 2005) and subsequent growth has been the focus of research for over 20 years (Litzow and Pellett, 1982; Watson and Himelick, 1982; Watson, 1985; Lauderdale et al., 1995; Gilman et al., 1998; and Struve et al., 2000). Watson (1985) postulated that over time smaller trees would surpass the overall size of large caliper trees and created a model based on differences in root to shoot ratios of 10.2 cm (4 in) and 25.4 cm (10 in) trees. During harvesting from the field, trees lose as much as 95% of the root system (Watson and Himelick, 1982), subsequently reducing the ability of the root system to provide adequate moisture and essential nutrients for proper photosynthetic function and tree growth. This postulation was supported by Gilman et al. (1998) and Lauderdale (1995), while Struve et al. (2000) suggested smaller trees will not outgrow larger trees over time. Species differences, geographic location, high mortality rates, and production methods were thought to be confounding factors in previous research (Watson, 2005). Litzow and Pellett (1982) suggested that *in situ* research quantifying the relationship of initial size and tree growth in the urban environment would enhance the application of previous reported findings.

Limited soil moisture availability (Bassuk and Whitlow, 1986), atmospheric moisture content (Cregg and Dix, 2001), and unique anthropogenic stress (Roberts, 1977) reduce tree growth and vigor in the urban forest (Close et al., 1996). Increased water stress, as a result of human activities on soil structure, texture, and composition (Craul, 1985 and Jim, 1998) is thought to be the leading cause of premature mortality of trees in the urban environment (Patterson et al., 1980 and Bassuk and Whitlow, 1986). Limitations of root growth caused by compacted soil have been suggested as a factor influencing the speed of establishment (Watson and Kupkowski, 1991). Understanding the influence of site conditions on establishment of different sizes of trees can be used to guide future planting and replacement efforts.

This study aims to characterize growth response and canopy development following transplanting of four different stock sizes 4.4 cm (1.75 in), 5.1 cm (2 in), 6.4 cm (2.5 in), and 7.6 cm (3 in) of balled-and-burlapped and one grade of bare-root tree 4.4 cm (1.75 in) while accounting for site and environmental conditions in the urban environment. Three species; Autumn Blaze maple (*Acer* x *freemanii* 'Autumn Blaze'), Bloodgood London plane tree (*Platanus* x *acerfolia* 'Bloodgood'), and swamp white oak (*Quercus bicolor*) were planted in four communities affected by the emerald ash borer infestation. The objectives of the study are to 1) quantify the influence of initial tree size on establishment and subsequent growth and development, 2) characterize the effects of the urban environment on tree growth, 3) provide recommendations to municipal arborists for increasing the efficiency of canopy restoration programs, and 4) provide additional data to test the hypothesis that smaller trees will outgrow larger trees. This study focused on the first two years of establishment and is a collaborative effort among Michigan State University, the USDA Forest Service, the Michigan Department of Natural Resources, the Michigan Nursery and Landscape Association, and the municipal forestry departments of the four corresponding communities.

Materials and Methods

Site Conditions

In April, 2006 three hundred trees were planted in four communities within the emerald ash borer quarantine area (Figure 1-1): Ann Arbor, Detroit, Lansing and

Rochester Hills. Sites were identified in conjunction with individual community forestry departments. The research plot in Ann Arbor was established at Fuller Park Pool and Recreation Area adjacent to the University of Michigan Medical Center. In Detroit the research plot was established at Romanowsky Park, a redeveloped urban site. Three locations were selected within Lansing; Mt. Hope and Evergreen Cemeteries and Fenner Nature Center. Trees were planted along roadsides in the cemeteries at Fenner Nature Center the trees were planted in an open field. In Rochester Hills all of the trees were planted in a 9 m (30 ft) wide traffic median along Hamlin road just south of I-75. Population and climate data are presented in Table 1-1.

Soil Testing

Twenty soil samples, each consisting of fifteen sub-samples collected from the top 30 cm (15 inches) of the soil profile at all sites, were analyzed for texture, fertility, and cation exchange capacity in October of 2007 at the Michigan State University Soil Testing Laboratory (Michigan State University, East Lansing MI). At the same time 20 soil core samples were collected from each of the Ann Arbor, Detroit, and Rochester Hills plots to determine the bulk density (Bd) of the existing soil. A total of 50 soil cores were collected in Lansing based on the heterogeneity of the multiple locations. A hammer driven soil coring device was used to acquire soil cores, and following oven drying soil cores for 15 days at 110°C, bulk density was recorded to the nearest 0.01 g/cm^3.

Rainfall and Moisture Content

Rainfall, estimated transpiration (PET), and temperature data were compiled from the Michigan Agricultural Weather Network. Water deficits were recorded when the inputs from rainfall and irrigation did not account for the water loss from transpiration and soil evaporation (Kramer, 1987). Ann Arbor, Detroit, Lansing, and Rochester Hills experienced long periods without a significant rainfall events of 22, 22, 39, and 13 days respectively. The greatest rainfall deficit in 2007 was recorded for the month of July in Lansing where estimated evapotranspiration was 127 mm greater than rainfall. The monthly rainfall deficit for July 2007 in Ann Arbor (54 mm) was less than half that of Lansing. All locations experienced rainfall deficits in June and July. In August the only site which continued to experience a water deficit was Rochester Hills (59 mm).

Experimental Design

Three species; Autumn Blaze maple (*Acer* x *freemanii* 'Autumn Blaze'), Bloodgood London plane tree (*Platanus* x *acerfolia* 'Bloodgood'), and swamp white oak (*Quercus bicolor*) were evaluated in this study. In order to reduce variance from production soils all trees were grown in a common soil type and purchased from Marine City Nursery (Marine City, MI). Caliper classes and corresponding soil ball sizes are in accordance with standard sizes based on the American Standards for Nursery Stock (American Nursery and Landscape Association, 2004). Baseline caliper, canopy volume, and individual leaf area data were collected in May and June of 2006 (Table 1-2). Analysis of baseline caliper measurements indicated that the 4.4 cm (1.75 in) bare-root London plane trees had a significantly greater caliper and was similar to the 5.1 cm (2 in) size classification. The 4.4 cm (1.75 in) and 5.1 cm (2 in) balled-an-burlapped oaks had initial caliper measurements of 6.07 ± 0.13 cm (2.39 ± 0.05 in) and 6.34 ± 0.16 cm (2.50 ± 0.06 in), respectively, and were not statistically different.

Tree locations were determined based on the community needs and complete blocks were not feasible at all four communities. Blocking of trees in Lansing consisted of five trees of each species representing all five size classifications. The Lansing location consisted of three sites with 15 *Quercus bicolor* planted in Fenner Park; 5 *Acer x freemanii* 'Autumn Blaze' in Mt. Hope; and 25 *Platanus x acerfolia* 'Bloodgood', 10 *Quercus bicolor*, and 20 *Acer x freemanii* 'Autumn Blaze' in Evergreen Cemetery. All of the other locations trees were planted in five randomized complete block designs consisting of a tree from each size class.

A Michigan State University team (MSU) coordinated and installed 300 trees using standard professional practice. Prior to installation, all trees were lightly pruned to remove all dead and potentially conflicting branches and the root flare was located within the root-ball. Bare-root trees were pruned heavier than balled-and-burlapped trees as is standard practice. In Ann Arbor, a Prentice™ crane was used to excavate soil from each planting pit, a Bobcat™ skid-steer dug planting pits in Lansing, and an auger was used in Rochester Hills. After the initial excavation, the MSU team finished all planting pits and planting by hand. All planting pits in Detroit were manually excavated and inert material such as bricks and concrete were removed. Following installation, all trees were mulched with a 7.6 cm (3 in) layer of municipal woodchips, top-dressed with a ½ cup of 10-20-20 granular fertilizer (LESCO), and well watered.

Subsequent maintenance was conducted by the MSU research team. Bi-weekly weeding and irrigation of 56.8L (15 US gal) was applied during the 2006 growing season at all locations. All dead and broken branches were removed throughout the season and trees were inspected for damage from insects and vandalism. At the end of the first growing season all mulch rings were top-dressed with an additional 2.5 to 5 cm (1 to 2 in) of wood chips to compensate for decomposition. In 2007, trees were not irrigated in accordance with typical cultural practice of each of the four communities.

Shoot Elongation

Terminal shoot elongation (cm) was measured following leaf abscission in 2006 and 2007. Five branches from the middle-canopy were tagged for identification and measurement. Due to the mortality of a few tagged branches it was necessary to select some replacement branches within the middle -canopy. In addition, branch caliper (mm) was collected at the origin of the each tagged branch using a digital caliper (Max-cal, Fowler, Newton, MA).

Relative Growth Rate

Initial trunk caliper were recorded 15 cm (6 in) above the trunk-soil surface following planting in May of 2006 using a digital. Recorded caliper measurements were the average of caliper measurements taken from east to west and from north to south. Location of caliper measurements were painted to ensure that caliper measurements collected in October of 2006 and November of 2007 were taken at the identical position. Relative growth rate was determined based on the trunk cross-sectional area where: r_n is the current radius of the trunk and $r_{(n-1)}$ is the radius of the trunk measured the previous season.

$$\{\pi r_n^2 - \pi r_{(n-1)}^2\}/\{\pi r_{(n-1)}^2\} \quad [1]$$

Individual Leaf Area

Ten, fully-expanded leaves were collected from the mid-canopy of all trees in June of 2006, 2007, and 2008. Leaf area (cm^2) was measured using a leaf area meter (LI-

300C, LI-COR Biosciences, Lincoln, NE) three times and averaged. The average of each sample was then divided by ten to acquire the average individual leaf area (cm^2).

Canopy Development

Crown height and crown width data were collected directly after planting in May of 2006. Canopies were measured again following leaf abscission in October 2006 and November 2007. Overall tree height and the width of the lower, middle, upper canopy, and height of the origin of the first branch on the trunk were measured using a measuring pole. Total canopy (m^2) was calculated as the summation of four descending cross-sectional areas with the following equations:

$$\mathbf{V_1=1/3\pi(h_1-h_2)} \tag{2}$$

$$\mathbf{V_2=1/3\pi(h_2-h_3)*(r_1^2+r_1r_2+r_2^2)} \tag{3}$$

$$\mathbf{V_3=1/3\pi(h_3-h_4)*(r_2^2+r_2r_3+r_3^2)} \tag{4}$$

$$\mathbf{V_4=\pi\ r_3^2\ (h_4-h_5)} \tag{5}$$

$$\mathbf{V_T=\sum(V_1\ V_2\ V_3\ V_4)} \tag{6}$$

Where h_1=total height, h_2=height of the upper canopy measurement, h_3=height of the middle canopy measurement, h_4=height of the lower canopy measurement, h_5=height of the origin of the 1st branch, and r_1=radius of the upper canopy, r_2=radius of the middle canopy, and r_3=radius of the lower canopy (Figure 1-2). Canopy volume was derived from the summation of additive frustra, or solid sections of a truncated cone and the contour of the canopy was calculated by additional measurements unlike typical growth indexes which include height and only two widths (Wright et al., 2006).

Light Interception

A quantum line sensor (LI-191, LI-COR BioSciences, Lincoln, NE) was used to measure the percentage of light intercepted by the tree canopy. Three readings were recorded and averaged to determine light levels without canopy interference before measurements were taken underneath each canopy. Three readings were taken 15 cm (6 in) below the first branch for each tree at mid-day (1000-14000 h) at each cardinal direction for a total of twelve measurements. Light interception was calculated as a percentage of total sunlight averaged from the twelve figures calculated without canopy interference.

Visual Assessment

In May of 2007 and 2008, trees were visually inspected and given a rank (scale 1-5) based on the overall quality of the canopy and amount of branch dieback. A rating of 1 was considered to be a dead or dying tree with major branch dieback or crown mortality, 2 was an unacceptable canopy with over 30.5 cm (12 in) of dieback prevalent within canopy or some death of major branches, 3 was an acceptable rating for trees that had dieback present primarily between 20.3 cm (8 in) and 30.5 cm (12 in) in length and very minor branch dieback, 4 was a fair rating with die-back of 7.6 cm (3 in) and 20.3 cm (8 in), and a rating of 5 was considered good and trees had little to no dieback exceeding 7.6 cm (3 in) .

Data Analysis

Initial analysis indicated significant species interactions therefore differences in growth rates of each species were analyzed separately. Canopy volume, relative growth rate, shoot elongation, leaf area were analyzed using a repeated measure analysis (Moser and Saxon, 1990) of PROC MIXED (SAS Inc., Cary, N.C.). Means were separated using Tukey's method when significant differences were indicated (α=0.05). Analysis of soil characteristics and environmental conditions were done also using PROC MIXED.

PROC CORR (SAS) was used to determine Pearson's correlation coefficient relating soil conditions; bulk density, pH, CEC, volumetric water content, and chemical compositions with tree growth and development, relative growth rate, change in canopy volume, leaf area, and shoot elongation. In addition, PROC CORR (SAS) was also used to correlate the visual ratings in 2007 with light interception, survival, shoot elongation, and visual ratings in 2008.

Results and Discussion

Soil Conditions

Soil chemical and physical properties varied among locations (Table 1-3). The main difference in soil textural composition was a lower clay fraction at the Lansing Fenner, location. The 4 % lower clay fraction may also be responsible for the lower cation exchange capacity 4.60 meq/100g at this location. A lower percentage of clay in the soil composition also limits micro-pore space therefore limiting the water holding capacity of the soil in Fenner Park. This difference was most notable in July 2007 when volumetric water content of the existing soil was more than 7% lower than the clay root ball.

Mean bulk density (Bd) varied between the soils of each of the locations. The highest mean bulk density of 1.67 g cm^{-3} was recorded at Rochester Hills where bulk densities ranged from 1.51 to 1.84 g cm^{-3}. Fenner, Mt. Hope, and Ann Arbor had the lowest bulk densities of 1.21, 1.18, and 1.14 g cm^{-3} respectively. The evergreen cemetery location in Lansing had a soil pH of 6.87. While acidic soils with a mean pH of 6.03 were measured at the Fenner location and the soils collected at Mt. Hope Cemetery, Detroit, and Rochester Hills were significantly more basic with pHs of 7.6, 7.6, and 7.92 respectively.

Survival

During the first two years of establishment, annual mortality rates of 1% and 1.5% were recorded for maples and planes respectively. These rates were lower than those previous observed in other studies of urban tree establishment (Sklar and Ames, 1985; Nowak et al., 1990; Ip, 1996; and Nowak et al., 2004). Maples lost during the study were the result of vandalism in Detroit. Oaks did not establish as well as the other two species with an annual mortality rates of 12 and 7.5% in 2006 and 2007.

In general, location and year did not influence survival of the trees. The higher mortality rates of oaks were the result of high rates of vandalism at the Detroit location, and lower soil moisture content at the Fenner location. These results are contrary to the 58% loss of the larger caliper red oaks (*Quercus rubra*) in the second year of the study conducted by Struve et al. (2002).

Canopy Growth and Development

Canopy volume increased with caliper size. However, there was no difference in initial canopy volume between the 6.4 cm (2.5 in) and 5.1 cm (2 in) oaks nor between the 5.1 cm (2 in) and both the bare-root and balled-and-burlapped 4.4 cm (1.75 in) sizes. Furthermore, the 7.6 cm (3 in) oaks in Ann Arbor had a mean canopy volume of 2.89 m^3 (102 ft^3), which was greater than all other size classes at Ann Arbor but was smaller than the mean canopy volume of the 7.6 cm (3 in) caliper trees at all other locations. Initial canopy volume of 7.6 cm (3 in) maples across all locations was 5.66 ± 0.31 m^3 (200 ± 10.95 ft^3) and larger than all the other sizes. The next largest mean canopy volume was that of the 6.4 cm (2.5 in) size classes, 3.71 ± 0.21 m^3 (131 ± 7.42 ft^3), which was only significantly greater than the 4.4 (1.75 in) sizes. The only London plane tree size classifications with similar initial canopy volumes were the 4.4 cm (1.75 in) balled-and-burlapped and bare-root.

The inability of a root system to provide adequate moisture to the canopy leads to an overall reduction in crown volume (Watson, 1985). Wide-spread canopy dieback during establishment suggests that trees are experiencing transplant shock (Struve et al., 2002). Prolonged canopy die-back reduces the impact a tree has on the surrounding landscape. In our study rate of canopy development was significantly influenced by size, location, and year.

We postulate that differences in response to transplant shock contributed to mean canopy loss in 2006 and 2007 of oaks and planes at all locations. In 2006, overall mean canopy volume of oaks declined in Ann Arbor, Detroit, Fenner Park, and Lansing by 9, 3, 9, and 24 % respectively. While the mean canopy volume of oaks in Rochester Hills increased by 1.5%. In 2007, the only locations which did not continue to experience volume loss greater than 25% were Detroit and Lansing. The location X size interaction was significant (p-value 0.0002) for oaks in 2007, perhaps as the result of continued declining canopy volumes of 4.4 cm (1.75 in) bare-root, 6.4 cm (2.5 in), and 7.6 cm (3 in) oak trees in Lansing by 55, 37, and 5%. The relative magnitude of the influence of initial size on canopy volume was lower in 2007 than when the trees were originally planted (Table 1-4).

After the first growing season all sizes of maples, oaks, and 7.62 cm (3 in) London plane trees decreased in canopy volume (Figure 1-3). Lauderdale et al. (1995) reported severe canopy die back of 7.6 cm (3 in) *Acer rubrum* 'October Glory' during the first two years of establishment. The first year after planting, 62.5% of the 7.6 cm (3 in) October Glory maples had lost more than 25% of their individual canopy volume.

In 2007, all sizes of maples and planes increased in canopy volume. Canopy volume of 4.4 cm (1.75 in) bare-root, 4.4 cm (1.75 in), 5.1 cm (2 in), 6.4 cm (2.5 in), and 7.6 cm (3 in) maples increased canopy volume by 118, 139, 120, 46, and 32% during the 2007 growing season. Mean canopy volume of London plane trees increased by 27, 45, 30, 26, and 13% for increasing size classes in 2007. With the exception of the 4.4 cm (1.75 in) bare-root and 5.1 cm (2 in) sizes, the mean canopy volume of oaks continued to decline. Swamp white oaks experienced the largest amount of canopy loss, in particular the larger sized oaks 6.4 cm (2.5 in) and 7.6 cm (3 in) which continued to lose canopy volume throughout the study (Figure 4). This was a result of a 50% loss of canopy volume of 7.6 cm (3 in) sizes across all locations and a 17 and 4% increases for the 4.4 cm (1.75 in) bare-root and 5.1 cm (2 in) sizes.

Larger size classes of maple and plane trees had a greater canopy volume at all locations. Significant location X size interactions were the result of increased canopy development of the maples in Lansing, Mt. Hope, and Ann Arbor in 2007. However, Rochester Hills was the only location in 2007 where the larger oaks 6.4 cm (2.5 in) and 7.6 cm (3 in) sizes had a greater mean canopy volume than the other sizes. The lack of different canopy volumes in oaks reflects the model presented by Watson (1985) and provides evidence that smaller oaks are subjected to less growth inhibition than larger oaks in the urban environment.

Canopy Quality

Measurements of light interception during the 2007 growing season and visual assessment following bud-break in 2007 and 2008 provided an indication of canopy quality. Ratings from the visual assessment after bud-break in 2007 were highly correlated (p-value <0.0001) with light interception, survival, shoot elongation, and visual ratings in 2008. Trees assessed as poor in 2007 had a reduced individual leaf area and reduced shoot growth relative to trees of the same species and size with ratings of fair and good.

Ratings of maples were not influenced by tree size and the year of assessment. The only significant factor in determining the assessment of the canopy was location (p-value <0.0001), with the lowest canopy quality of 4.08 at Rochester Hills. Differences in mean visual assessment of oaks varied by location and size over time (p-values of 0.0009 and 0.0294). Ratings for oaks in Rochester Hills in 2008 were the lowest of all locations with a rating of 2.65. The largest sized oaks 7.6 cm (3 in) had a mean assessment rating of 2.1 for 2007 and 2008. The 4.4 cm (1.75 in) bare-root and balled-and-burlapped and 5.1 cm (2 in) sizes had the highest rating in 2007 and 2008. London plane trees were significantly influenced by the interaction of year and tree size (p-value 0.0004). The highest visual assessment in both 2007 and 2008 was the 5.1 cm (2.2 in) size classification with ratings of 4.6 and 4.3. The only significant differences in canopy quality based on visual assessment were between the 5.1 cm (2 in) size classification and the 6.35 cm (2.5 in) and 7.6 (3 in) sizes in 2007 and the 7.6 cm (3 in) size in 2008.

Many of the benefits provided by the urban canopy are the result of shade or the percentage of light intercepted by the canopy (McPherson et al., 1997 and Nowak et al., 2002). Reductions in temperature (McPherson, 1994), rainfall intensity (Dwyer et al., 1992), and windspeed (Oke, 1989) are enhanced by the quality of the canopy. Periodic defoliation is a symptom of transplant shock (Struve and Joly, 1992) and when trees are defoliated their impact is compromised. Additional water and nutrients are required for the canopy to "re-flush" following the loss of leaves. The process of re-foliation adversely affects trunk growth, and the loss of foliage adversely impacts radial growth (Rose, 1958) and can lead to mortality (Kulman, 1971 and Dobbertin, 2005).

Initial tree size influenced the amount of light intercepted by the canopy for all species in June and July, but was only a significant factor in determining the light interception of maples in August (Figure 1-4). In June, the 4.4 cm (1.75 in) bare-root size which only intercepted 51% of light while all other sizes intercepted more than 10% more light. All sizes of maples intercepted less light in July than in June. In August both the 4.4 cm (1.75 in) and the 5.1 cm (2 in) size class increased the percentage of light interception. Larger caliper 6.4 cm (2.5 in) and 7.6 cm (3 in) trees intercepted 67 and 64% in July and close to 60% in August. The only size which did not intercept a similar amount of light in August was the 4.4 cm (1.75 in) bare-root size.

In June of the 7.6 cm (3 in) sized oaks indicated significantly less light interception than the 4.4 cm (1.75 in) and 5.1 cm (2 in) balled-and-burlapped trees. The larger oaks intercepted 37% of light while the 4.4 cm (1.75 in) and 5.1 cm (2 in) balled-and-burlapped trees intercepted 57 and 62% of light in June respectively. In August the amount of light intercepted by the canopy did not differ by size (p-value .5093).

Shade provided by London plane trees was directly influenced by initial size classification in June and July. In June, the 4.4 cm (1.75 in) trees intercepted 40% of light which was the lowest amount of interception among all the sizes. All size classes experienced a reduction in canopy cover between June and July (Figure 1-7). There was no longer a difference in the amount of shade provided across size classes in August.

Site location influenced the quantity of light intercepted for all species in June and July. In August, the amount of light intercepted by maples and planes was significantly influenced by site location (p-values of 0.0075 and <0.0001). Maples in Rochester Hills intercepted 10% less light than trees at all of the other locations. Mt. Hope was the only location where there was no evidence of defoliation and light interception went from 70 to 72% from June to July. Other locations all experienced a decline in the amount of light intercepted, however, maples at the Lansing Evergreen and Detroit location continued to intercept more light than those in Rochester Hills. In August, the only location which still intercepted significantly more light than Rochester Hills (47%) was Lansing (61%).

The amount of light intercepted by oak trees in June was significantly greater at Ann Arbor (61%) than at Rochester Hills (42%). A reduction in light interception was recorded for oaks at all locations, and the greatest difference in mean light interception was observed at Lansing where the amount of light intercepted went from 54% to 36%. In July, oaks across all sizes at Fenner and Ann Arbor intercepted significantly more light than in Rochester Hills. By August there was no longer a difference in light interception between all sizes of oaks.

London plane trees in Ann Arbor, Detroit, and Lansing intercepted 63, 55, and 67% of light, while planes in Rochester Hills only intercepted close to 30%. The significantly lower percentage was perhaps a result of defoliation in the previous year which limited the capacity of the trees to refoliate in 2007. The percent of light intercepted by planes in Lansing was significantly greater than Rochester and Ann Arbor in July, and all other locations in August. These differences were most likely attributed by the ability of planes in Lansing to refoliate in August while defoliation continued to decrease the amount of light intercepted at all other locations.

Total Canopy Impact

The limitations of removing dead trees from statistical analysis when evaluating the differences in tree size evaluations can confound conclusions about the impact of a size class which may have high mortality rates. Therefore, a canopy volume ratio in relation to the total volume of species was calculated for each size class, which incorporated the influence of mortality (Figure 1-5). The ratio incorporates the differences in canopy volume due to canopy dieback and mortality. Results from this analysis provide the relative value of the impact provided by planting larger trees.

Total canopy volume of maples, oaks, and planes planted in April 2006 was 297 (10, 488 ft^3), 234 (8, 263 ft^3), and 470 m^3 (16,5 97 ft^3). Initially the majority of the canopy volume was provided by the larger caliper trees (Figure 1-5). Net canopy volume planted in 2006 was 1,001 m^3 (35, 350 ft^3) which decreased during the 2006 growing season by 81 m^3 (2, 860 ft^3) then in 2007 the cumulative canopy increased to 1,048 m^3 (37, 010 ft^3). The contribution of smaller trees to the cumulative total canopy increased for maples, oaks, and planes after the first two years of establishment. Canopy dieback, mortality, and lower rates of canopy development reduced the impact of 7.62 cm (3 in) caliper maples, oaks, and planes by 18, 34, and 9% during the first two years of establishment (Figure 1-5). In contrast, the relative impact of smaller caliper trees increased in 2007 for all three species. Increases of 4.8 and 2.3% were measured for the contribution of the 4.4 cm (1.75 in) bare-root and 5.1 cm (2 in) maples respectively. While the influence of the largest caliper and 4.4 cm (1.75 in) bare-root sizes of London plane trees decreased. The 7.6 cm (3 in) oaks had the largest drop in total canopy volume by nearly 20%. Conversely the total canopy volume of 5.1 cm (2 in) size class oaks increased by close to 7.5 %. The composition of London plane trees was not as dynamic as the maples and oaks. During the first two years of establishment the percent composition of the total canopy volume provided by the largest sized 7.6 cm (3 in) caliper maples, oak, and planes decreased by and 6.7, 19.5, and 3.5%, respectively.

Extrapolation of the ratio, can guide future size selections of *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' in canopy restoration programs. Over time the impact of different caliper trees can be measured by their contribution to the total canopy volume planted at a location. Optimal sizes can be selected based on their ratio of canopy development. For instance, it would be more efficient to plant a 4.4 cm (1.75 in) oak than a 7.6 cm (3 in) oak which had a reduction of 20% in its contribution to the total canopy volume across all locations.

Shoot Elongation

Shoot elongation for each species was significantly influenced by location and size in 2006 and 2007 (p-values <0.0001), and the interaction between size and location was only significant for maples in 2006 (p-value 0.0012) (Figure 1-6). Overall shoot elongation of maples significantly increased after the second year (p-value <0.0001) by nearly 3 fold. Mean shoot elongation of oaks decreased from 66 (26) to 55 cm (22 in) and the Bloodgood London plane trees did not differ between 2006 and 2007 (p-value 0.6008). In 2006, 4.4 cm (1.75 in) balled-and-burlapped and bare-root plane trees had nearly double the shoot elongation (19.6 and 17.0 cm) than all the size classes combined. Mean shoot elongation of the 4.4 cm (1.75 in) size London plane trees declined from 17 cm in 2006 to 14.3 cm in 2007. The 7.6 cm (3 in) balled-and-burlapped plane trees had significantly less shoot growth (7.3 cm) than smaller caliper 4.4 cm (1.75 in) bare-root and balled-and-burlapped sizes in 2007. Initial tree size influenced shoot elongation in 2006 for all species and for maples and plane tree in 2007.

Elongation of terminal shoots is an important indicator of tree establishment (Watson et al., 1986 and Struve et al., 2000). Species dependent responses of twig growth in response to transplant shock were presented by Watson et al. (1986), with a reduction in growth lasting an average of three years. Results of the influence of initial size of *Quercus bicolor* were consistent with the previous evaluation of *Quercus rubra* (Struve et al., 2000). They observed similar shoot elongation of transplanted and non-transplanted oaks the first year after planting, however a reduction in shoot extension in transplanted red oaks occurred the second year after planting. Larger caliper oaks had more than twice the shoot elongation relative to smaller oaks the first year after transplanting, while over the next two years smaller trees had significantly greater stem growth (Struve et al., 2000).

The inverse relationship was reported by Lauderdale et al. (1995) when comparing the stem elongation of 3.8 cm (1.5 in) and 7.6 cm (3.0 in) *Acer rubrum*

‘October Glory’. Smaller trees doubled the amount of shoot elongation from 11.4 cm (4.5 in) to 22.4 cm (8.8 in) while the shoot elongation of the larger trees decreased from 6.1 to 5.5cm. A reduction in shoot elongation over an extended period of time indicates that the root system of the smaller trees are establishing at a faster rate (Lauderdale et al., 1995). In 2006, mean shoot elongation of the 4.4 cm (1.75 in) bare-root and balled-and-burlapped maples were 9.7 (3.8) and 6.9 cm (2.7 in) respectively. Mean shoot elongation of these size classes was nearly triple that of the 6.4 cm (2.5 in) and 7.6 cm (3 in) sizes with means of 2.3 and 2.8 cm of growth. Unlike the previous study by Lauderdale et al. (1995) the mean shoot elongation of the larger caliper 6.4 cm (2.5 in) and 7.6 cm (3 in) maples did not decrease in 2007, however they remained significantly less than the mean shoot growth of the 4.4 cm (1.75 in) balled-and-burlapped size classification.

Trunk Growth

Trunk growth of maples, oaks, and planes was influenced by size (p-values of <0.0001, 0.001, and <0.00001) and year (p-values of <0.0001, 0.0006, and <0.0001). During our study, location significantly influenced the trunk growth of maples (p-value <0.0001) and planes (p-value <0.0001), and the only time when the location X size interaction was significant was for maples in 2006. Trunk growth was characterized by differences in the relative growth rate to account for increased trunk cross-sectional area rather than caliper (Figure 1-7). Maples, oaks, and planes increased relative growth rates from 0.07, 0.05, and 0.10 in 2006 to 0.20, 0.01, and 0.18 in 2007.

Differences in trunk growth among size classifications indicate different responses to transplant shock. Differences between smaller and larger caliper trees were reported for oaks, maples, and planes in both 2006 and 2007 (Figure 1-7). The 4.4 cm

(1.75 in) bare-root and 5.1 cm (2 in) trees had greater trunk growth than the 7.6 cm (3 in) trees which had the lowest relative growth rate of 0.04. Relative growth rate of both bare-root and balled-and-burlapped 4.4 cm (1.75 cm) maple trees was greater than all other size classes in 2006. Relative growth rates of the 4.4 cm (1.75 in) bare-root and balled-and-burlapped sized maple trees were 0.29 and 0.27 in 2007. After the first two years of establishment, the larger caliper 6.4 cm (2.5 in) and 7.6 cm (3 in) sized trees had the least amount of trunk growth with relative growth rates of 0.12 and 0.11.

Smaller caliper size classifications having a greater relative growth rate was consistent with the results found in the London plane trees. In 2006, the 4.4 cm (1.75 in) size planes had a relative growth rate of 0.16 and 0.11 for the balled-and-burlapped and bare-root size classes, respectively, and were significantly greater than the mean relative growth rate of the 6.4 cm (2.5 in) size. The trend of smaller caliper trees having a greater relative growth rate continued in 2007, when the 6.4 cm (2.5 in) and 7.6 cm (3 in) had relative growth rates three times less than that of the mean relative growth rate of the 4.4 cm (1.75 in) balled-and –burlapped trees. The trend was not as apparent for oak trees. Different sized oaks had similar growth rates in 2006, however in 2007 there were significant differences between the initial sizes. The 5.1 cm (2 in) oaks had a mean relative growth rate of .13 which was greater than the .04 relative growth rate of the 7.6 cm (3 in) size.

Location significantly influenced maples and planes, however it was not a factor in determining the relative growth rate of oaks (Figure 1-8). In 2006 the relative growth rate of maples in Lansing (0.12) was significantly greater than all the other locations.

Similarly the relative growth rate of planes was greater in Lansing than all locations except Ann Arbor in 2006 and all locations in 2007.

Leaf Size

Leaf size decreases when water is limiting and is an important indicator of transplant stress (Parkhurst and Loucks, 1972). Individual leaves differed by initial tree size, year, and the interaction of size and year for all three species of trees. Location only influenced the mean leaf size of maples (p-value <0.0001). Mean leaf size of maples, oaks, and planes increased after the first year of establishment by 85, 95 and 57% respectively. Mean leaf size in Rochester Hills was 26.8 cm^2 (4.15 in^2), 42.1 cm^2 (6.52 in^2), and 25.1 cm^2 (3.89 in^2) in 2006, 2007, and 2008. In 2008, mean leaf size of maples in Rochester Hills was less than in 2006, perhaps as a result of increased water stress in 2007. The 40% reduction in leaf size in 2008 at Rochester Hills corresponded to the location with the least conducive soil conditions.

Mean individual leaf area increased for all three species from 24.8 (3.8), 32.9 (5.1), and 37.5 cm^2 (5.8 in^2) in 2006 to 45.8 (7.1), 64.1 (9.9), and 58.7 cm^2 (9.1 in^2) in 2007 for maples, oaks, and planes. We postulate that the increase in leaf size is the result of root expansion during the first year and the ability for the new root system to provide more water and nutrients to the crown developing in 2007. The reduction observed in 2008 in consistent with the findings of Struve and Joly (1992) which observed a reduction in leaf size as a response to transplant shock in red oak (*Quercus rubra*) seedlings.

In 2008, the mean leaf size of 6.4 cm (2.5 in) and 7.6 cm (3 in) maples were significantly smaller than the 4.4 cm (1.75 in) balled-and-burlapped and bare-root sizes

(Figure 1-9). In 2006, the mean individual leaf area of the bare-root London plane trees was 70.9 cm^2 more than twice the size of any other size class. In 2007, the leaf size of the bare-root London plane trees remained significantly larger than the rest of the sizes, and the 4.4 cm (1.75 in) and 5.1 cm (2 in) sizes had larger leaves than the 6.4 (2.5 in) and 7.6 cm (3 in) sizes, perhaps as a response to the heavier pruning they received before planting. However, in 2008 the mean leaf size only for the 4.4 cm (1.75) bare-root and balled-and-burlapped trees were 78.6 (12.2) and 63.8 cm^2 (9.9 in^2) remained significantly larger than the 7.6 cm (3 in) size which had a mean of 45.2 cm^2 (7.0 in^2).

The bare-root oaks had a mean leaf size of 22.3 cm^2 (3.5 in^2)in 2006 which was significantly less than all other size classes. In 2007 size was not a significant factor in determining leaf size (p-value .2399). In 2008, the 4.4 cm (1.75 in) bare-root trees and 5.1 cm (2 in) sizes had respective leaf sizes of 70.4 (10.9) and 57.8 cm^2 (9.0 in^2)which were both greater than the 36.1 cm^2 (5.6 in^2) leaf size of the 7.6 cm (3 in) size. The dramatic change in leaf size of the 4.4 cm (1.75 in) bare-root trees was the result of the death of the three trees within the size classification after the first year.

Tree size influenced the individual leaf area of maples collected in 2008 (p-value 0.0006). The second year after transplanting, the smaller 4.4 cm (1.75) bare-root and balled-and- burlapped tree sizes had a mean leaf size of 40.8 (6.3) and 38.3 cm^2 (5.9 in^2) respectively. Leaf size of the larger sized maples of 6.4 (2.5 in) was 31.5 cm^2 (4.9 in^2) and 7.6 cm (3 in) caliper was 28.2 cm^2 (4.4 in^2) both of which were significantly smaller than the smaller caliper trees.

Influence of Location

Differences in growth and canopy development at each of the corresponding communities were best exemplified by variation of their soil composition (Table 1-3) and rainfall deficits (Figure 1-10), which affected soil volumetric water content (Figure 1-11). Results from our correlation analysis (Table 1-5) indicate that soil bulk density, pH, and calcium concentration were all highly correlated with differences in canopy growth and development during establishment. Bulk densities as high as 1.86 g cm^{-3} 30.46 g in^{-3} were reported at Rochester Hills, which is much greater than the 1.6 gcm^{-3} 26.21 g in^{-3}threshold at which root growth is limited (Zisa, 1980). Reductions in the rate of root development adversely affect the ability of a tree to uptake water even when there is adequate soil moisture present (Watson and Himelick, 1982). Furthermore high calcium concentrations (2626) ppm and a mean soil pH of 7.92 contributed to the lower growth in comparison to the other locations.

In 2006 relative growth rate was negatively correlated with pH and calcium concentration and in 2007 was also correlated with bulk density and cation exchange capacity (Table 1-3). Canopy development was unaffected by soil conditions in 2006, while in 2007 canopy development bulk was highly correlated with density, pH, cation exchange capacity, and calcium concentration. The reduced rate of canopy development observed at Rochester Hills was the highly correlated with of greater bulk density and elevated pH. Without supplemental irrigation in 2007 the correlations between soil conditions and canopy and trunk growth were exacerbated (Table 5).

Conclusion

Differences in soil composition at each location primarily bulk density, pH, and calcium concentration, were found to have significant negative correlations with tree growth in 2007. The lack of, and inability for root systems of larger trees to supply the canopy with water was characterized by decrease light interception of the trees in July of 2007 at all locations and further exemplified the differences in establishment rate of larger vs smaller trees.

Results from the study indicate that there is a definitive relationship between tree size and canopy growth in development in the urban environment. Over the course of the study overall canopy volume of larger trees generally remained greater than the smaller trees, however, differences in rate of canopy development, branch growth, and relative growth rate suggest that smaller trees appear to have a minimized duration of transplant shock in comparison larger trees. In addition, the canopy composition of total canopy of each species indicates that smaller maples and oaks provide are a more substantial component two years after planting. Subsequent data will provide more evidence to evaluate the postulation of Watson (1985) that smaller trees outgrow larger trees over time. Our study emphasizes the need for municipal arborist to take initial size into consideration in future canopy restoration programs.

Tables and Figures

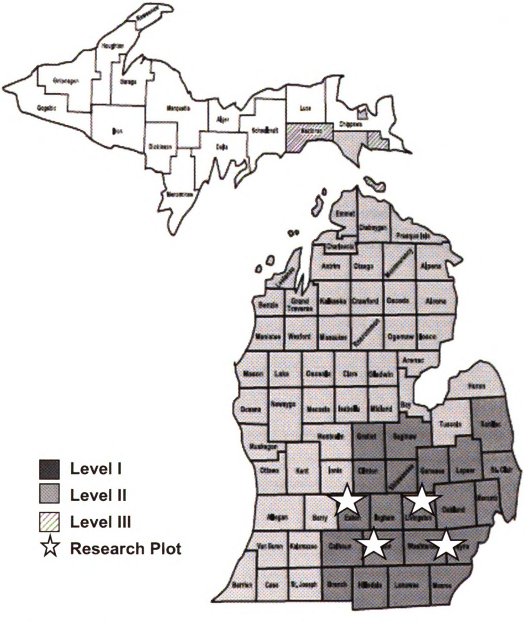

Figure 1-1. Location of research plots within the Emerald Ash Borer Quarantine revised February, 2008 by the Michigan Department of Agriculture.

Table 1-1. Population and 30-year temperature and precipitation within research communities

Municipality	Population	Highest Monthly Mean Temperature (July)		Lowest Monthly Mean Temperature (January)		Annual Precipitation	
		°C	°F	°C	°F	mm	In
Ann Arbor	114,498	22.7	72.9	-4.6	23.8	872.0	35.3
Detroit	911,402	22.8	73.1	-4.8	24.3	833.4	32.8
Lansing	118,379	21.6	70.9	-5.6	21.9	800.6	31.5
Rochester Hills	68,754	22.6	72.6	-4.9	23.2	765.8	30.2

All population data collected from United States Census Bureau 2003 Estimates

Weather data collected based on 30-yr means from 1971-2001

Ann Arbor, Detroit, and Lansing weather information collected from weather stations within each city

Weather data for Rochester Hills was the average of data collected in Pontiac and Shelby Township

Table 1-2. Baseline measurements of 4.4 cm (1.75 in) bare-root (BR) and balled-and-burlapped, 5.1 cm (2 in), 6.4 cm (2.5 in), and 7.6 cm (3 in) caliper and canopy volume planted in four Michigan communities

Species	Size	Caliper (cm)	Caliper (in)	Canopy Volume (m^3)
Acer x *freemanii* 'Autumn Blaze'				
	BR	^{x}5.10 ± 0.07 d	2.01 ± 0.03 d	1.44 ± 0.17 c
	1.75	4.99 ± 0.10 d	1.97 ± 0.04 d	1.91 ± 0.32 c
	2	5.89 ± 0.08 c	2.32 ± 0.03 c	2.14 ± 0.12 c
	2.5	6.34 ± 0.08 b	2.49 ± 0.03 b	3.71 ± 0.21 b
	3	7.43 ± 0.08 a	2.93 ± 0.03 a	5.66 ± 0.31 a
Quercus bicolor				
	BR	4.76 ± 0.14 d	1.87 ± 0.06 d	0.54 ± 0.07 c
	1.75	6.07 ± 0.13 c	2.39 ± 0.05 c	1.19 ± 0.11 c
	2	6.34 ± 0.16 c	2.50 ± 0.06 c	1.33 ± 0.07 bc
	2.5	7.05 ± 0.12 b	2.77 ± 0.05 b	2.04 ± 0.10 b
	3	9.15 ± 0.18 a	3.60 ± 0.07 a	6.64 ± 0.72 a
Platanus x *acerfolia* 'Bloodgood'				
	BR	6.28 ± 0.15 c	2.47 ± 0.06 c	2.34 ± 0.18 d
	1.75	5.07 ± 0.13 d	1.99 ± 0.05 d	2.28 ± 0.24 d
	2	6.53 ± 0.09 c	2.57 ± 0.03 c	3.61 ± 0.25 c
	2.5	8.07 ± 0.12 b	3.18 ± 0.05 b	6.36 ± 0.32 b
	3	8.65 ± 0.10 a	3.41 ± 0.04 a	8.93 ± 0.45 a

^{X}means separated within columns of each species using Tukey's adjustment ($\alpha=0.05$)

Table 1-3: Soil chemical and physical properties in four communities in Michigan

Location	Texture (%)			Chemical Composition (ppm)				CEC	(Bd)
	Sand	Silt	Clay	pH	P	K	Ca	meq/100g	gcm^{-3}
Lansing: Fenner Park	83 a	13 b	4 b	6 d	76 a	66 c	578 c	4.6 c	1 ab
Lansing: Mt. Hope Cemetery	73 a	17 ab	10 ab	7.6 ab	13 ab	67 c	1873 bc	12 ab	1 ab
Lansing: Evergreen Cemetery	67 a	22 a	11 ab	6.9 c	12 b	56 c	1312 bc	8.7 bc	1 c
Ann Arbor	66 a	21 ab	13 a	7.5 bc	42 ab	136 b	2434 a	14 ab	1 ab
Detroit	62 b	25 a	13 a	7.6 ab	15 b	200 a	2526 a	15 a	1 bc
Rochester Hills	67 a	21 ab	13 a	7.9 a	8 b	75 c	2626 a	14 a	2 d

All soil samples were analyzed at the Soil Science Laboratory at Michigan State University

Means within a column followed by the same letter are not different (α=0.05).

Means separated by Tukey's range test

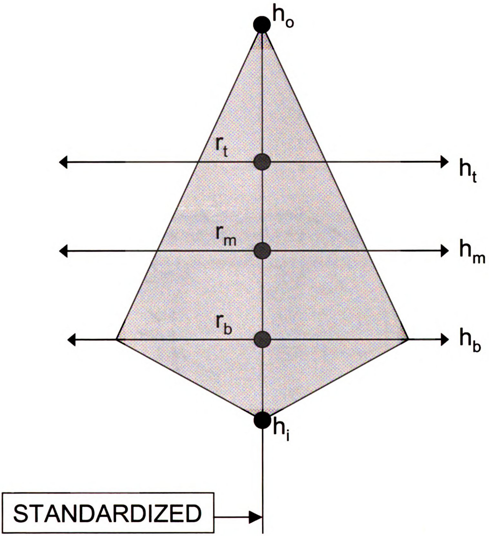

Figure 1-2. Canopy volume measurements of total height (h_o), height of the upper canopy (h_t), middle canopy (h_m), lower canopy (h_b), height of the origin of the first branch(h_i), and the radii of upper canopy (r_t), middle canopy (r_m), and lower canopy (r_b)

All measurements standardized 6 inches above the root-soil surface interface
Measurements were taken from east to west and from north to south and averaged

Table 1-4. F-values of the influence of size (S), location (L), and time (T) on mean canopy volume during the first two years following transplanting

	Maples		Oaks		Planes	
S	119.92	***	86.33	***	151.07	***
L	10.82	***	4.80	**	18.76	***
T	156.84	***	18.76	***	41.31	***
S x L	2.40	**	3.83	***	2.87	**
S x T	0.74	NS	15.13	***	0.56	NS
L x T	16.84	***	0.89	NS	25.71	***
S x L x T	1.94	**	1.07	NS	1.36	NS

*,**,*** represent significance with p-values of 0.05, 0.01, and <0.0001 respectively

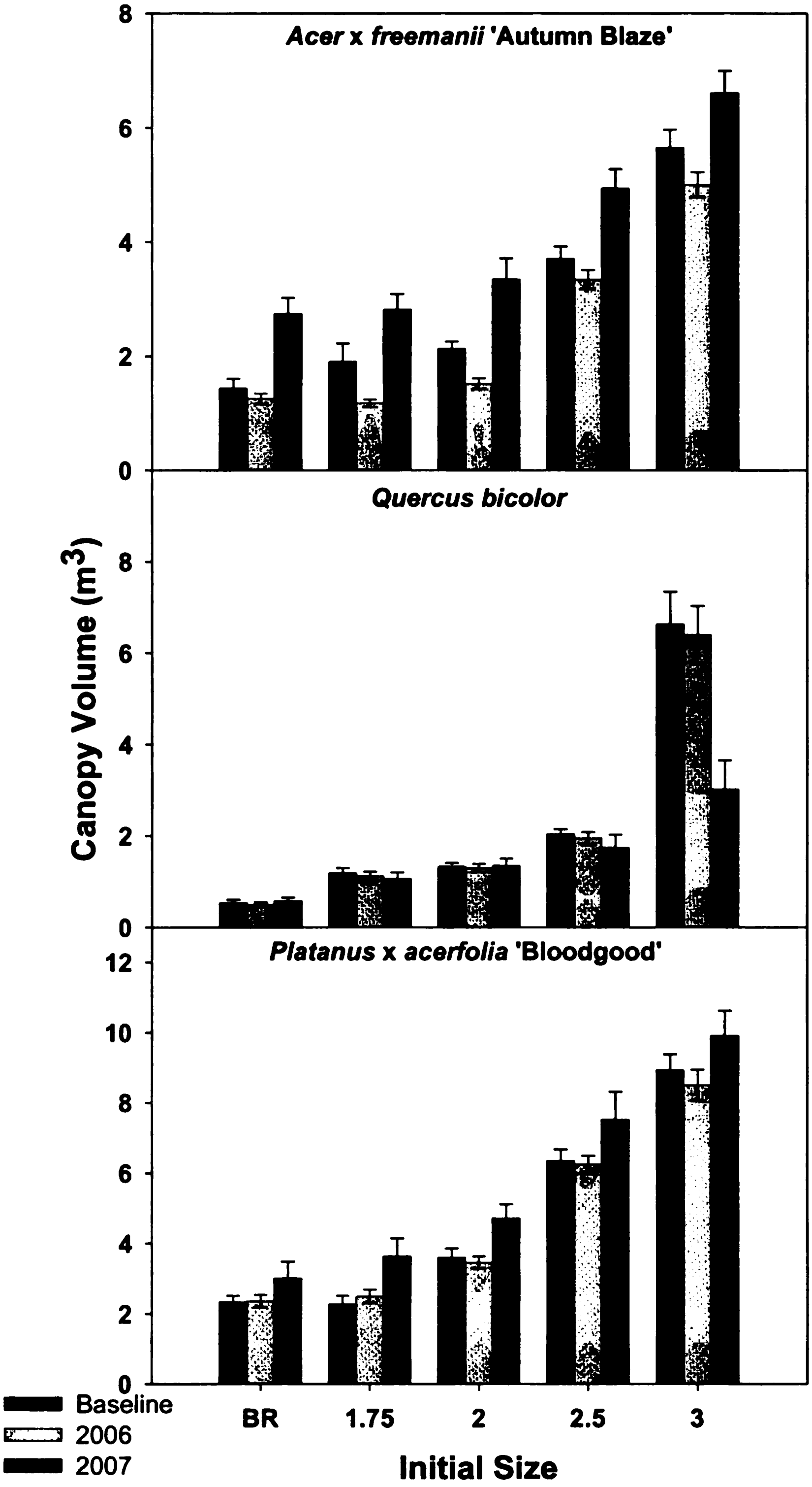

Figure 1-3. Canopy volumes of *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' by size during the first two years of establishment

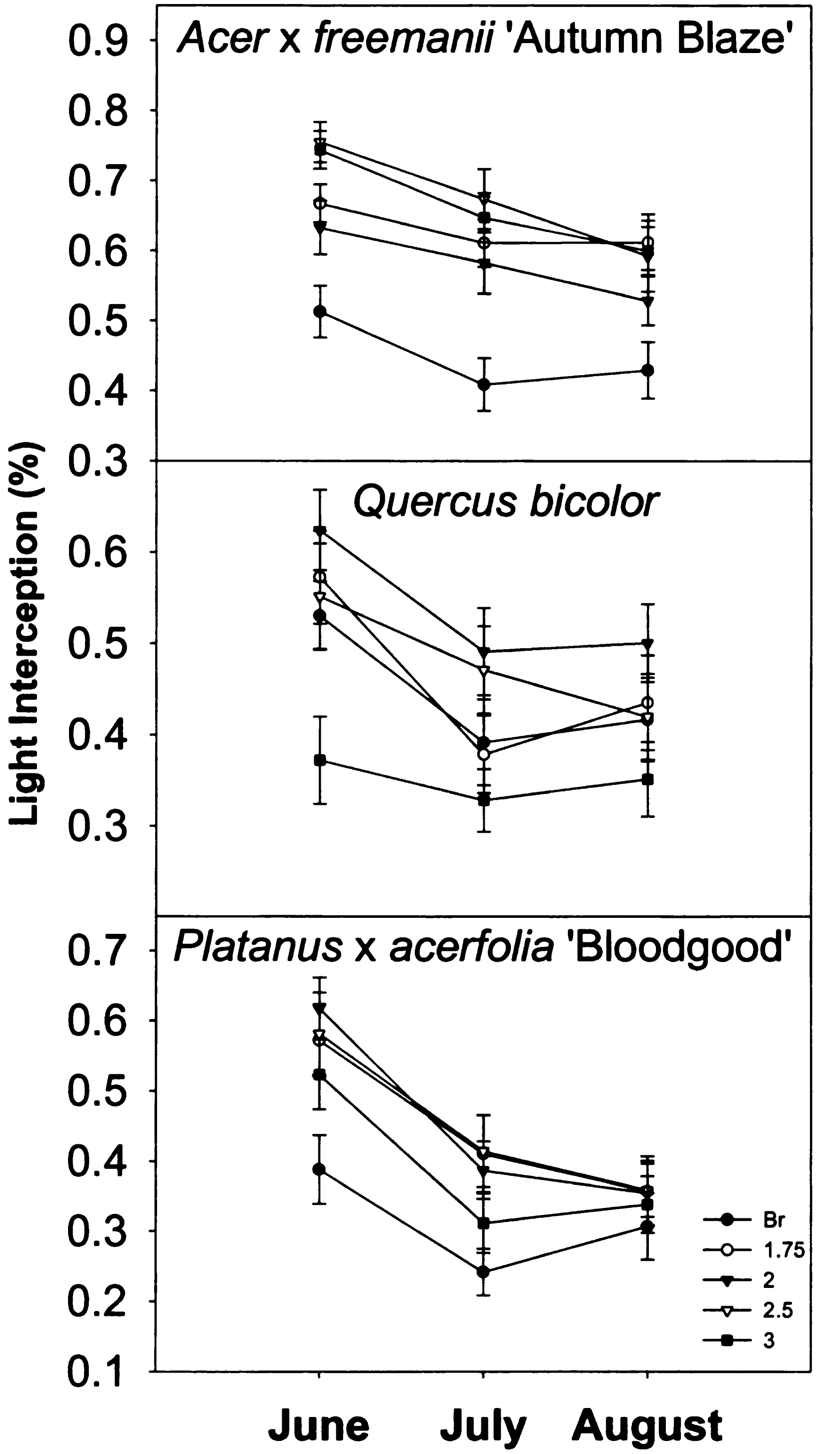

Figure 1-4. Influence of month and size on light interception of *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' pooled across all locations for June, July, and August of 2007

BR represents the 4.4 cm (1.75 in) bare-root initial size

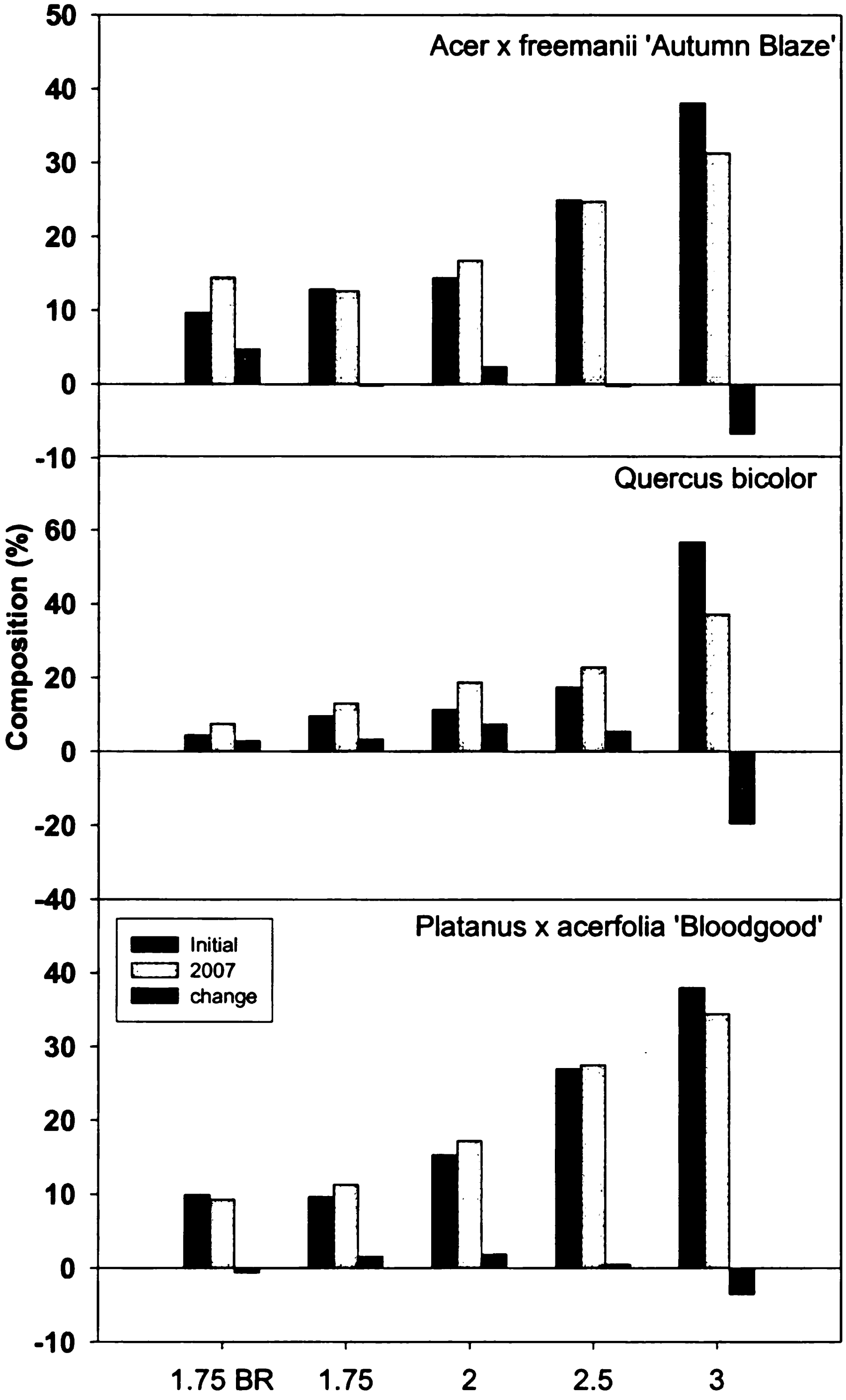

Figure 1-5. Composition of total canopy volume and % change of each species over a two year period based on initial size classification

BR represents the 4.4 cm (1.75 in) bare-root initial size

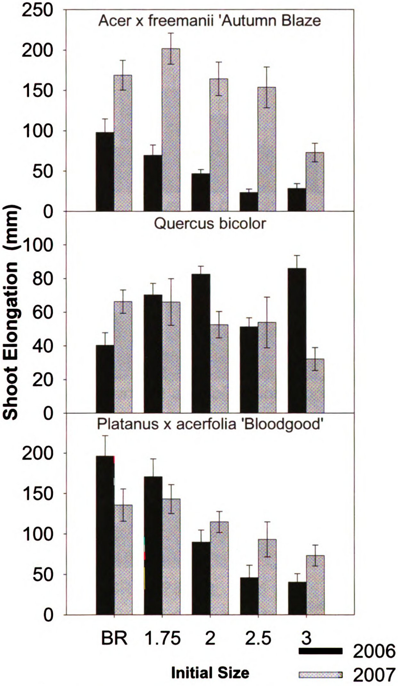

Figure 1-6. Mean shoot elongation (mm) of five branches within the middle canopy of three species for growth in 2006 and 2007

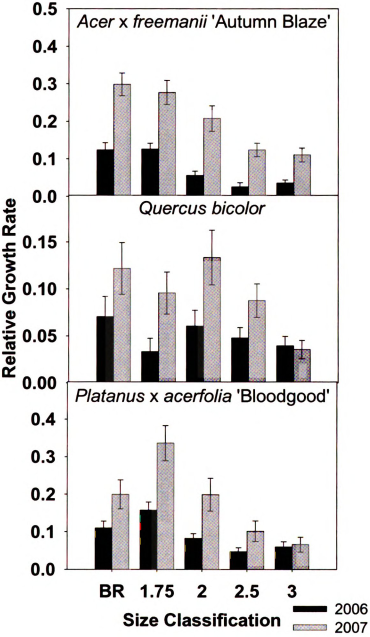

Figure 1-7. Influence of initial tree size on relative growth rates of *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, *Platanus* x *acerfolia* 'Bloodgood' during the first two years of establishment in four Michigan Communities

Relative growth rate is the increase of trunk cross sectional area divided by initial trunk cross sectional area

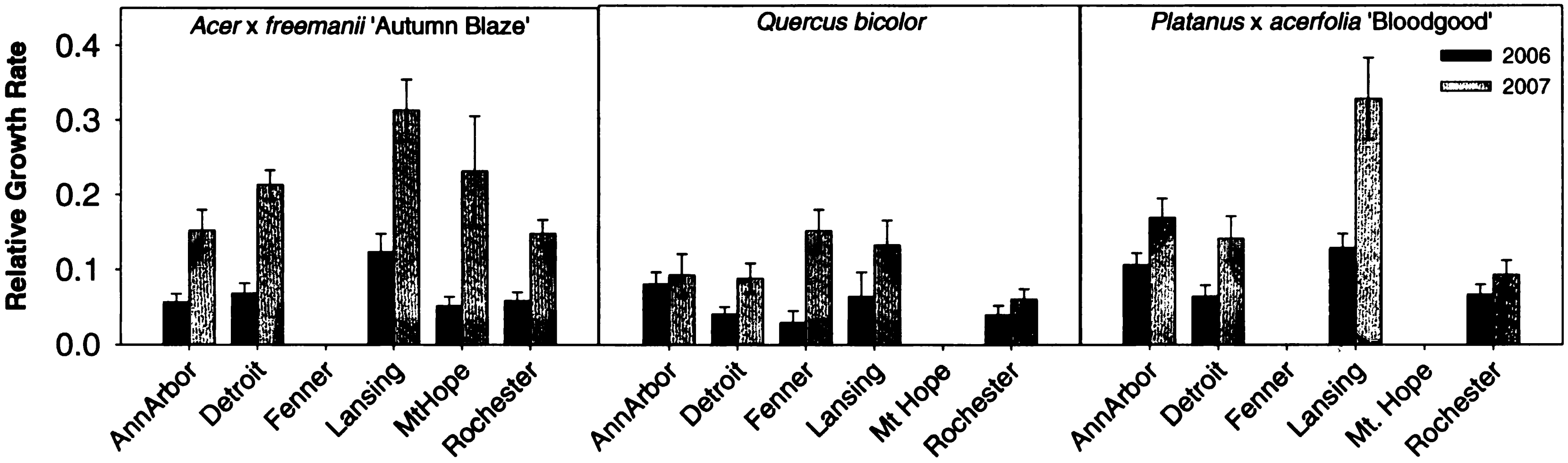

Figure 1-8. Influence of site location on the relative growth rate of *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' during the first two years of establishment

Relative growth rate is the increase of trunk cross sectional area divided by initial trunk cross sectional area

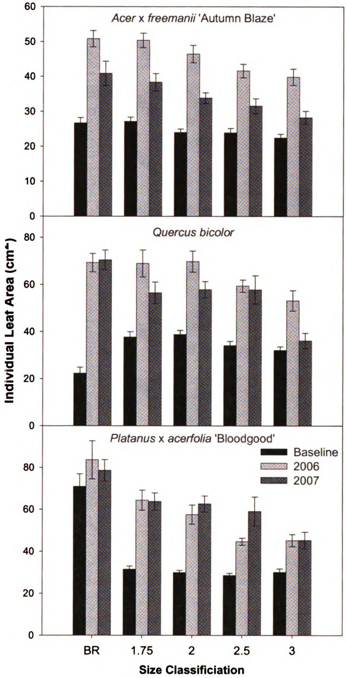

Figure 1-9. Individual leaf size (cm2) of three species during the first two years of establishment in four Michigan communities based on tree size classification

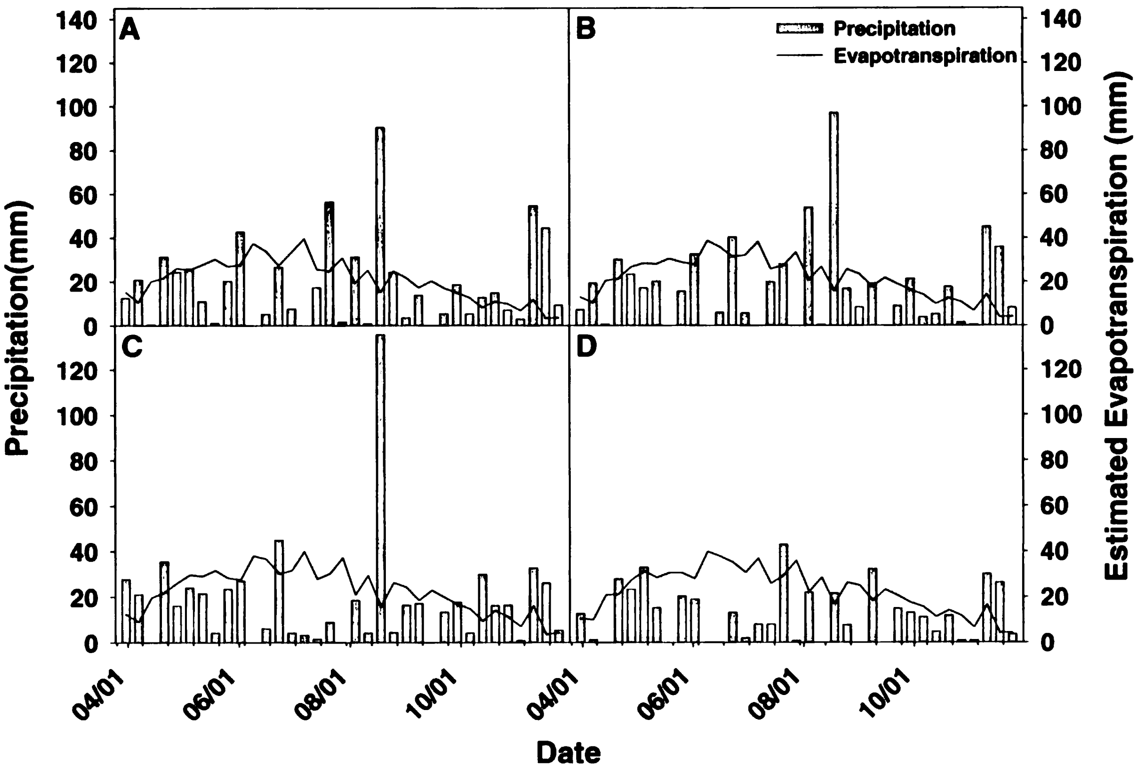

Figure 1-10. Rainfall deficit, precipitation, and estimated evapotranspiration of (A) Ann Arbor, (B) Detroit, (C) Lansing, and (D) Rochester Hills, MI from 4/1/2007 to 10/31/2007

Estimated evapotranspirational loss data collected from the Michigan Agricultural Weather Network
Rochester Hills precipitation data is average of reported precipitation in Pontiac and Shelby Township, MI
Estimated evapotranspirational water loss for Detroit is mean of Lapeer and Dundee, MI agricultural centers

Table 1-5. Correlation coefficients of the relationship between soil conditions; bulk density (Bd), pH, cation exchange capacity (CEC), and concentration of calcium (Ca) with tree growth and canopy development; relative growth rate (RGR), visual assessment rating (VR), light interception (LI), leaf area (LA), branch growth (BG), and canopy volume (VOL) across four Michigan communities

	Bd		**pH**		**CEC**		**Ca**	
RGR1	-0.089	NS	-0.148	*	-0.121	NS	-0.135	*
RGR2	-0.144	*	-0.358	***	-0.342	***	-0.370	***
VR	-0.154	**	-0.071	NS	-0.019	NS	-0.054	NS
ΔLI1	0.122	*	0.052	NS	0.026	NS	0.034	NS
ΔLI2	0.177	**	0.080	NS	-0.012	NS	-0.001	NS
ΔLA	0.043	NS	0.093	NS	0.116	NS	0.123	*
ΔBG	0.137	*	0.096	NS	0.091	NS	0.106	NS
ΔVOL1	-0.071	NS	-0.059	NS	-0.066	NS	-0.058	NS
ΔVOL2	-0.242	***	-0.276	***	-0.244	***	-0.253	***

*, **, and *** represent significance with respective p-values of ≤0.05, ≤0.01, ≤0.0001

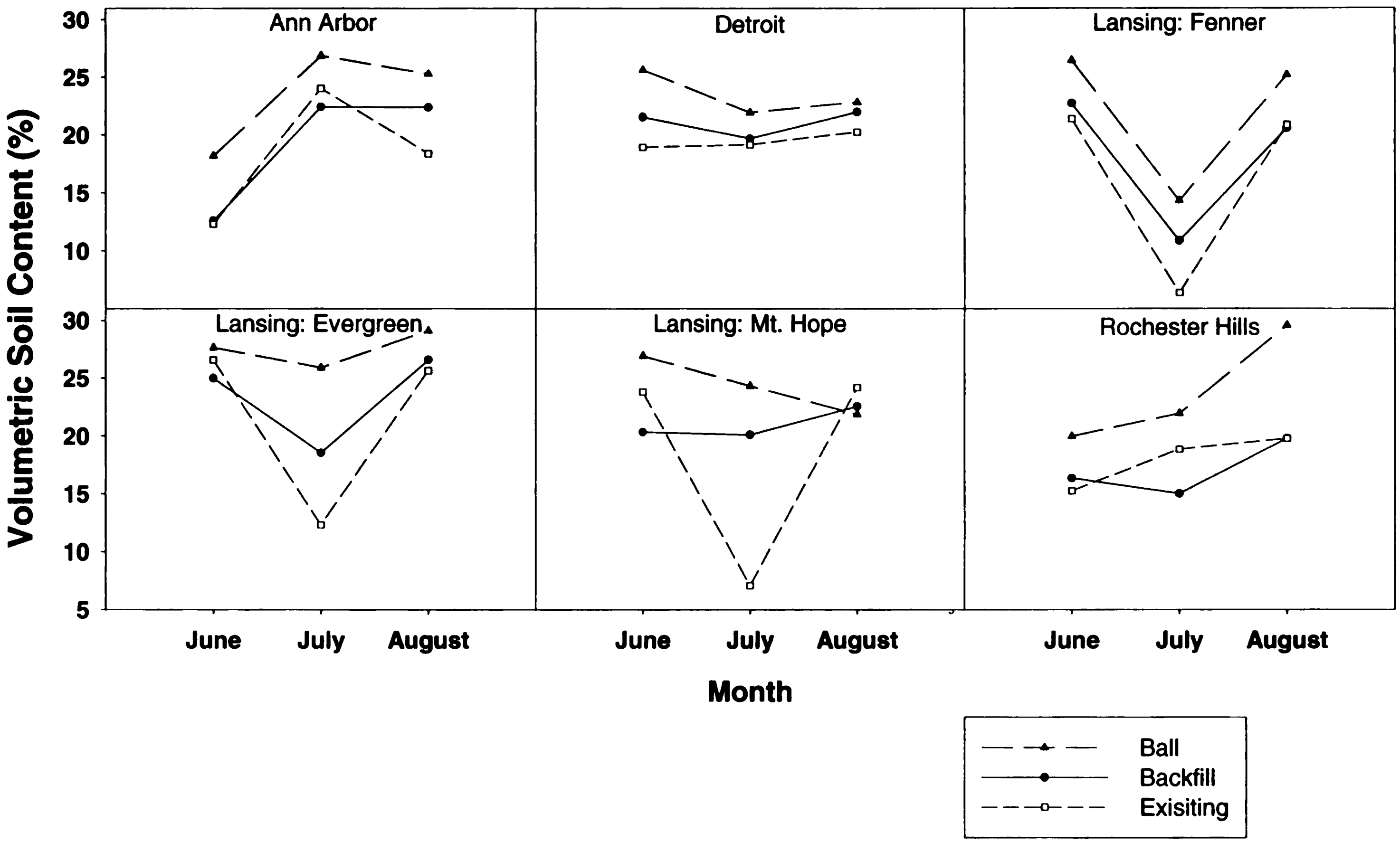

Figure 1-11. Monthly volumetric water content at Ann Arbor, Detroit, Lansing: Fenner, Evergreen, and Mt. Hope locations, and Rochester Hills, MI in 2007

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CHAPTER TWO

INFLUENCE OF INITIAL STOCK SIZE AND EXISTING SOIL CONDITIONS ON GAS EXCHANGE AND PRE-DAWN MOISTURE POTENTIAL OF TREES IN THE URBAN ENVIRONMENT

Prepared for Submission to Arboriculture and Urban Forestry

INFLUENCE OF INITIAL STOCK SIZE AND EXISTING SOIL CONDITIONS ON GAS EXCHANGE AND PRE-DAWN MOISTURE POTENTIAL OF TREES IN THE URBAN ENVIRONMENT

Additional key words: Acer x *freemanii* 'Autumn Blaze', *Platanus* x *acerfolia* 'Bloodgood', *Quercus bicolor*, rainfall deficit, stomatal conductance, transpiration, and urban soils.

Abstract

In a companion study the influence of initial stock size on the growth and canopy development of three tree species was evaluated in four Michigan communities. Results from the first year after planting suggest that smaller trees established at a quicker rate than larger trees. This study was conducted to evaluate the potential influence of initial stock size on gas exchange and pre-dawn moisture potential of recently planted oaks, London plane trees, and maples. Initial stock size had no effect on the net photosynthesis and only influenced stomatal conductance and transpiration of oaks on one of three dates of collection. However, difference in site conditions affected gas exhancge and pre-dawn moisture potential for all species throughout 2007 (p-values <0.0001). In addition, a seasonal trend of increasing water deficit was observed at the Lansing locations, with mean pre-dawn moisture potentials as low as -1.92 MPa (-19.21 bars) for 6.1 cm (2.5 in) oaks. Results indicate that differences between trees sizes and tree growth and canopy development during the first two-years did not significantly influence gas exchange.

Introduction

Sub-optimal growth conditions (Berrang, 1985; Oke et al., 1989; and Iles, 2003), high mortality, and limited life spans of urban trees (Foster and Blaine, 1978) all pose a threat to the continued health of the urban forest. Trees in the urban environment are subjected to additional stresses when compared to trees grown in natural forest ecosystems, which limit their growth and development potential (Roberts, 1977; Kozlowski, 1985; Lauderdale et al., 1995; and Close et al., 1996). In addition to similar abiotic and biotic pressures present in their native environment, stress in the urban landscape increases precipitously with human development (Bassuk and Whitlow, 1986).

A multitude of soil (Craul, 1985; Jim, 1998; and DeKimpe et al., 2000) atmospheric (Whitlow and Bassuk, 1988; Cregg and Dix, 2001), and environmental (Kozlowski, 1987 and Oke et al., 1989) causes have been correlated with limited plant growth in the urban environment (Roberts, 1977; Clark and Kjelgren, 1990; Whitlow et al., 1992; and Close, 1996). High soil bulk density and degraded soil structure, as a result of compaction, limit soil water availability for urban trees (Jim, 1998 and DeKimpe et al., 2000). In addition to reduced infiltration from soil compaction, atmospheric drought can result in decreased plant water potential (Kozlowski, 1987 and Whitlow et al., 1992) and subsequently suppressed growth. Atmospheric deficits also increase transpiration water loss, reduce the rate of water absorption by the root system, and decreasing net photosynthesis.

Previous research evaluating the water relations of urban trees has focused on comparing trees uniform in age (Whitlow et al., 1992) and equivalent in size (Kjelgren and Clark, 1993 and Cregg and Dix, 2001). These studies suggest that water stress in the urban environment is highly variable and that trees grown in these conditions are subjected to additional stress, when compared to trees grown in a park or forested environment. In addition, Lauderdale et al. (1995) reported an inverse relationship between initial stock size and tree physiology. Smaller *Acer rubrum* 'October Glory', 3.8 cm (1.5 in), trees had higher net photosynthesis, transpiration, leaf conductance, and water use efficiency than larger caliper 7.6 cm (3 in) trees during the first two years following planting.

Water composes the majority of the fresh weight of trees, is essential for proper physiological function, and acts as a solvent for gas and mineral exchange for the maintenance of turgor. Kramer (1987) attributed the role of water stress in tree growth to a water imbalance between deposits from irrigation and rainfall and withdrawals caused by soil evaporation and transpiration from the canopy. The balance between water deposits and withdrawals is responsible for the delayed growth. Furthermore, the alterations in transpiration during periods of low water potentials are species dependent (Kozlowski and Davies, 1975). Therefore, it is necessary to evaluate several species to validate the effect of water stress for a given ecosystem. Trees experiencing water stress increases their susceptible to pest infestation (Cregg and Dix, 2001), decreased shoot growth (Close et al., 1996), and reduces photosynthetic production (Lauderdale et al., 1995).

Indicators of water stress include an overall reduction of tree size, trunk growth, and individual leaf area. Over 30 years ago, Kozlowski and Davies (1975) postulated that stomatal closure is the primary factor reducing transpiration while experiencing water stress and suggest that rapid stomatal closure following exposure to increased light intensity minimizes water loss. Prolonged water stress, referred to as drought stress, has varying effects on plant growth and development. The primary effects are the inhibition of photosynthesis, the loss of turgor pressure, and reduction of metabolism of carbohydrates and nitrogen. While secondary effects include a reduction in cell size, and increased stomatal closure.

Pre-dawn plant moisture potential has also been directly correlated to differences in soil moisture content (Kozlowski, 1982 and Whitlow et al., 1992). A three year study of street trees in New York City suggested that seasonal changes in pre-dawn plant moisture content was directly attributed to similar changes in soil moisture content, while trends of midday plant moisture potential were a function of atmospheric demand. The results of the study further indicated that cumulative water deficits are prevalent in the Northeastern United States.

This study aims to quantify the influence of initial stock size on tree physiology in the urban environment. Soil structural, chemical, and textural composition was correlated with net photosynthesis, stomatal conductance, and transpiration will provide insight into previously reported conclusions (Ross, 2008). The objectives of this study are to 1) test the hypothesis that smaller trees establish at a quicker rate than larger trees, 2) determine if there is a relationship between initial stock size and net photosynthesis, stomatal conductance, and transpiration, 3) quantify the influence of stock size on pre-dawn moisture stress during the establishment of urban trees, and 4) evaluate potential correlations of physiological responses to differences in soil and environmental conditions. Results from this study will be used to determine if growth response of trees in the urban environment are a function of gas exchange and pre-dawn moisture potential.

Materials and Methods

Experimental Design

Research plots in four communities within the emerald ash borer quarantine, Detroit, Ann Arbor, Lansing, and Rochester Hills, were established in April of 2006. Trees were monitored during the 2006 growing season to quantify the influence of initial stock size on canopy growth and development. The three species, *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfloia* 'Bloodgood', planted at the research plots represent potential replacements for ash (*Fraxinus* sp.). 93 oak trees, 100 maples, and 99 plane trees broke bud in 2007 and were utilized in this study. The size classification of stock sizes selected for evaluation (Ross, 2008) : 3" caliper B&B (balled and burlapped), 2 ½" caliper B&B, 2" caliper B&B, 1 ¾" caliper B&B; and 1 ¾" caliper bare-root. Soil conditions for each of the four locations were analyzed in October of 2006 and differences were discussed by Ross (2008).

A Michigan State University team coordinated and installed 300 trees using standard professional practice. Prior to installation, all trees were lightly pruned to remove all dead and potentially conflicting branches. The bare-root trees were pruned heavier than the balled-and-burlapped trees. In Ann Arbor, a Prentice™ crane was used to excavate the soil from each planting pit, a Bobcat™ skid-steer dug the holes for all of the planting pits in Lansing, and an auger was used in Rochester Hills. All planting pits were finished by hand digging after initial excavation by the MSU team at all locations.. All planting pits in Detroit were manually excavated and inert material such as bricks and concrete were removed from the planting pit. Following installation, all trees were mulched with a 7.6 cm (3 in) layer of municipal woodchips, top-dressed with a ½ cup of 10-20-20 granular fertilizer (LESCO), and well watered.

Subsequent maintenance was conducted by the MSU research team. Bi-weekly weeding and irrigation of 56.8L (15 US gal) was applied during the 2006 growing season at all locations. All dead and broken branches were removed throughout the season and trees were inspected for damage from insects and vandalism. At the end of the first growing season all mulch rings were top-dressed with an additional 2.5 to 5 cm (1 to 2 in) to compensate for decomposition. In 2007, the trees were not irrigated in accordance with the cultural practices of each of the four communities.

Photosynthesis, Transpiration, and Stomatal Conductance.

During the 2007 growing season photosynthesis (P_n), transpiration (E), and stomatal conductance (G_s) were analyzed using a portable CIRAS-2 photosynthesis system with a PLC6 circular leaf cuvette measuring 2.5cm^2 of leaf area (PP Systems, Amsbury, Massachusetts). Gas exchange was measured at the same time as soil volumetric water content at all locations. Measurements were taken from a single leaf within the mid-canopy for each of the trees in June, July, and August of the 2007 growing season at each of the research plots. Gas exchange was measured at each of the sites independently during mid-day (1000-1400 h).

Volumetric Soil Moisture Content

Monthly measurements of volumetric soil moisture content at 15 cm (6 in) were monitored using a Trase Systems 1 model 6050X1 (Soil Moisture Equipment Corporation, Santa Barbara, California) time domain reflectometer, with a sampling error of ±2%. Due to compacted soil conditions at all locations, an alignment block and slammer were required for the proper insertion of two 15 cm stainless-steel waveguides. Volumetric moisture content of the root-ball was collected 15 cm from the trunk, backfill measurements were taken at the midpoint of the edge of the planting pit and the rootball, and undisturbed soil was monitored 30 cm from the edge of the planting pit.

Pre-Dawn Moisture Potential

Pre-dawn moisture potentials (ψ) were collected from the Lansing sites during the 2007 growing season, on July 5, July 24, August 15 – 17. Sub-samples of two fully expanded leaves from the middle-canopy were analyzed from each of the 75 trees on July 5th and 24th. In order to complete all measurements between 0200 and 0500h, a sample size of two leaves were collected. After initial analysis of the July data, the sample size was expanded to five leaves samples in an attempt to separate the means of each size classes by decreasing sampling variability. The increase in samples size prevented collection in one session and pre-dawn moisture content was monitored species independently over a three day period from August 15-17. Samples were analyzed in the field between 0200 and 0500 h using a portable pressure chamber model B (Soil Moisture Equipment Corporation, Santa Barbara, California) immediately after leaves were removed from the tree as suggested by Blum et al. (1973).

Analysis

Seasonal trends of gas exchange rates, pre-dawn moisture potentials, and volumetric soil content was analyzed using the PROC MIXED function in a repeated measure design using SAS version 9.1.3 (SAS Institute Inc., Cary, N.C.). The influence of initial size, species, location, time of year, and all interactions were reported with a .05

significance level (α=0.05). Significant differences of means were separated using Tukey's adjustment (SAS). Differences in soil characteristics between site locations and rainfall deficit were acquired using PROC MIXED without a repeated measure design.

The relationship of soil chemical, structural, and textural characteristics and tree physiology was analyzed using the PROC CORR function (SAS). Correlations between bulk density, cation exchange capacity, % sand, volumetric water content, and pH with monthly transpiration, photosynthesis, stomatal conductance were reported in a Pearson's correlation matrix.

Results and Discussion

Data analyzed from 300 trees planted in four urban Michigan communities (Ross, 2008) quantified the influence of initial trees size on tree growth and canopy development. Results from this companion study suggested that one cause for the difference in tree growth and canopy development could be the result of alterations in physiological function. This study was conducted to better examine if initial tree size had an influence on gas exchange and pre-dawn moisture potential.

Photosynthesis, Stomatal Conductance, and Transpiration

In our study, month, location, and interactions of month and location affected the gas exchange of all three species. Species independent analysis, indicates that size is not a significant factor in determining the net photosynthesis of maples (p-value 0.6218), oaks (p-value 0.1813), and planes (p-value .1757). Furthermore, when data is analyzed for each species for each month only the transpiration and stomatal conductance of the oak trees are significantly influenced by initial tree size.(p-value 0.0008). In July the only significant difference of transpiration was between the 4.4 cm (1.75 in) bare-root and 6.5 cm (2.5 in) oaks with means of 2.8 and 1.73, respectively. Stomatal conductance of oaks in July also was significantly influenced by tree size (p-value .0312).

In general, the relative magnitude of the influence of location diminished over time (Table 2-1). Stomatal conductance and transpiration of London plane trees and stomatal conductance of Autumn Blaze maples were no longer affected by location in August. Oak trees planted in Rochester Hills had the lowest rate of photosynthesis when compared to all other locations perhaps as a result of the high bulk density, pH, and concentration of calcium (Ross, 2008). In addition photosynthesis, stomatal conductance, and transpiration of all three species was lowest in Detroit in June. A greater increase in photosynthesis in subsequent months in Detroit coupled with a reduction in Lansing from June to July affected the differences in site locations. The photosynthetic rate of plane trees was no longer influenced by site location in August.

An inverse relationship between initial tree size of *Acer rubrum* 'October Glory' and gas exchange was suggested by Lauderdale et al. (1995). Net photosynthesis, transpiration, and stomatal conductance were greater in smaller caliper trees throughout the first two years of establishment. In their study, mean photosynthesis in August of the smaller caliper trees was 9.0 and 12.8 $\mu molm^{-2}s^{-1}$ while the larger caliper trees had net photosynthesis of 5.1 and 8.7 $\mu molm^{-2}s^{-1}$ during the first two years of establishment. It was suggested that the difference in gas exchange between 3.8 cm (1.5 in) and 7.6 cm (3 in) sized red maples was the result of smaller trees having a faster rate of establishment than the larger caliper trees (Lauderdale et al. 1995).

Influence of Urban Soils on Tree Physiology

Correlations between soil conditions and the growth and canopy development of the trees in this study suggest that soil conditions were influential in determining growth and canopy development during the 2007 growing season (Ross, 2008). There were significant correlations of gas exchange with differences in soil conditions (Table 2-2). Results from the correlation analysis indicate that soil conditions were more influential in determining the physiological functions of the trees in June and August. In addition, there was not a significant correlation between average volumetric soil moisture content or soil texture and gas exchange in July. Furthermore there was a strong correlation between stomatal conductance and soil conditions. This is a unique phenomenon that may the result of different vapor pressures at each of the locations which were responsible for the differences in stomatal conductance. Cregg and Dix (2001) and Bassuk and Whitlow (1996) both suggested that the water stress is not solely dependent upon soil moisture content.

The most abundant and strongest correlations were observed for the month of June when transpiration and photosynthesis were correlated with chemical, textural, and structural soil parameters except for bulk density (Table 2-2). The chemical component of soils which had the least correlation was magnesium which is probably the result of average concentrations at all locations. Soil moisture had the strongest correlation with stomatal conductance and transpiration in July when the Lansing and Detroit locations had the lowest volumetric water content (data not shown).

Two of the more interesting significant correlations presented are that of the relationships between pH and calcium with tree physiology. Negative correlation coefficients suggest that as soil pH and calcium concentration increase, the physiological function decreases. The strongest correlation of -.46, described the inverse relationship between soil pH (p-value <0.0001) and the stomatal conductance (p-value >0.0001) in June. Transpiration in June had the strongest negative correlation with calcium concentrate with a coefficient of -.52 (Table 2-2). Therefore transpiration decreased in soils with a higher concentration of calcium.

Pre-dawn Moisture Content

Pre-dawn moisture potential has a negative effect on net photosynthesis and stomatal conductance (Ritchie and Hinckley, 1975), however pre-dawn moisture potential and gas exchange measurements were not taken on the same day. We were un able to monitor pre-dawn moisture stress at all locations. However site location had a significant effect on volumetric water content in June, July, and August of 2007 (p-values of <0.0001 for all months) and rainfall deficits were wide-spread during 2007. In addition to monitoring pre-dawn moisture stress, quantifying the vapor pressure deficit (Bassuk and Whitlow, 1986 and Cregg and Dix, 2001) and the soil/ root water potential (Reich and Hinckley, 1989) should be considered. Reich and Hinckley (1989) concluded pre-dawn moisture potential collected from leaves was not a significant factor in determining differences in the gas exchange of blackjack oak (*Quercus marilandica* Muenchh.) and northern red oak (*Quercus rubra* Lam.).

Pre-dawn moisture potentials measured in June and July indicated species differences (p-value <0.0001); however size was only an influential factor for maples in July (p-value 0.0449). Although not statistically significant, data from June and July suggested that tree size may influence the pre-dawn moisture potential of maples and planes. Analysis of data separated by species and time further support this relationship. We postulated that the numerical differences exhibited in June and July could be further investigated by increasing the sample size from two to five leaves and the f-values of the effect of tree size on pre-dawn moisture potential increased as the season progressed (Table 2-3). Increasing the sample size prevented the collections of data from all 75 trees in the Lansing location during one session between 0200 and 0500h. Our treatment of interest was size and preliminary analysis of data had already determined that each of the three species had different levels of pre-dawn moisture potential.

The increased influence of size on pre-dawn moisture stress suggests that as the stress of trees increased from a seasonal deficit. Unlike the 3-year study of street trees in New York which only had a difference of -1.0 mPa (Whitlow et al., 1992), pre-dawn moisture potentials became more negative in July and August. This increasing pressure potential indicates a seasonal deficit in water availability. Means of each size, were separated by species, and are presented in Table 2-4. In June, there was no significant influence of initial size on pre-dawn moisture potential and in July, size was only an influential factor in determining pre-dawn moisture potential of maples. Despite the significance of tree size in determining pre-dawn moisture potential of maples in July (p-value 0.0449), means were not able to be separated by size classification.

In August, sample size was increased from the original measurement of two leaves from each tree collected in a single night to five leaves per tree over the course of three nights. Increasing the sample size prevented data collection and measurement of all trees between 0200 and 0500 h, due to the distance between sites and equipment availability. Maples were collected on August 15, planes on August 16, and oaks on

August 17, which prevented statistically analyze species differences, however the influence of size of pre-dawn moisture potential for maples and oaks were significant (p-values of 0.0006 and ≤0.0001).

The 7.6 cm (3 in) maples had the greatest, most negative, mean pressure potential of -8.83 which was significantly greater than that of the 5.1 cm (2 in) and 6.4 cm (2.5 in) size which had pressure potentials of -7.05 and -6.86 respectively (Figure 2-1). The 6.4 cm (2.5 in) oaks had the greatest, most negative, pre-dawn moisture potential -19.21 bars. Pressure potentials of the 4.4 cm (1.75 in) bare-root, 4.4 cm (1.75 in) balled-and-balled, and 5.1 cm (2 in) were -10.34, -11.48, -15.88 bars. Except for the 7.6 cm (3 in) size (-11.1 bars), as the initial tree size of oaks increased from 4.4 cm (1.75 in) to 6.4 cm (2.5 in), the pressure potential increase suggesting that larger trees had a greater demand for water than smaller trees (Figure 2-1). During 2006, two of the three 7.6 cm (3 in) had died and been removed from the study. The loss of these trees may have been the reason why the 7.6 cm (3 in) oaks did not have a greater mean pressure potential than the other sizes.

Adequate sample size may not be the only contributing factor in the separation of means in August. A higher rainfall deficit in Lansing in August could have increased the degree of stress of trees during the establishment process further exacerbating the differences in pressure potentials. Between data collection on July 24 and August 15 there was a cumulative rainfall deficit of 62 mm.

Conclusions

The results from this study suggest that the influence of stock size on canopy growth and development are not influenced by the physiological parameters we monitored. The influence of initial stock size on tree growth and development were more significant than the influence of initial stock size on gas exchange (Ross, 2008). In general, shoot elongation, trunk growth, leaf area, and canopy development were found to be greater for smaller caliper trees (Ross, 2008). Our original postulation that the increased growth was caused by increased photosynthetic production was not supported by data collected during the second year of establishment.

There is a strong relationship between urban tree gas exchange and site conditions. During the first two years of establishment, differences in photosynthesis, stomatal conductance, and transpiration were all significantly influenced by urban soil conditions. The relationships between soil chemical, structural, and textural characteristics and tree physiology were most evident in June and August. Further research is needed to quantify the relationship between urban soils and tree physiology, although the homogeneity of these soils and their exogenous sources remain a challenge.

The results from the analysis of pre-dawn potentials indicate that the lack of irrigation and below average precipitation in June and July in 2007 for all sites resulted in a seasonal water deficit. The seasonal water deficit was measured by increasing pressure potentials during July and August. Furthermore, when evaluating the influence of tree size on pre-dawn moisture potential an increase in sample size from two to five leaves proved to be an effective. The urban environment presents a unique challenge to forestry research and the complexity of *in situ* studies requires further investigation in order to determine if the relationships concluded from controlled research are to be applied.

Tables and Figures

Table 2-1. F-values of net photosynthesis (P_n) and stomatal conductance (G_s) of Autumn Blaze maple (*Acer* x *freemanii* 'Autumn Blaze'), swamp white oak (*Quercus bicolor*), and Bloodgood London plane (*Platanus* x *acerfolia* 'Bloodgood') the second year after being transplanted at four different locations in Michigan

					P_n						G_s			
Species	**Effects**	**DF**	**June**		**July**		**August**		**June**		**July**		**August**	
Autumn Blaze maple														
	Size	4	0.9	NS	0.4	NS	0.2	NS	0.6	NS	0.5	NS	0.6	NS
	Location	4	47.8	***	4.1	**	3.8	*	44.5	***	4.0	**	1.4	NS
	SxL	16	1.2	NS	1.1	NS	0.5	NS	1.1	NS	1.1	NS	0.3	NS
Swamp white oak														
	Size	4	1.0	NS	1.4	NS	1.4	NS	1.6	NS	2.9	*	1.4	NS
	Location	4	25.1	***	6.6	**	7.8	***	30.5	***	6.9	**	8.4	***
	SxL	16	1.1	NS	1.0	NS	0.4	NS	1.4	NS	0.8	NS	0.6	NS
Bloodgood London plane														
	Size	4	2.5	NS	1.6	NS	0.4	NS	1.0	NS	1.0	NS	1.3	NS
	Location	3	67.7	***	10.6	***	0.3	NS	24.7	***	2.9	*	1.8	NS
	SxL	12	1.5	NS	0.6	NS	1.0	NS	0.9	NS	0.7	NS	1.4	NS

*, **, *** p= 0.05, 0.01, and 0.0001 respectively

Table 2-2. Correlation of soil characteristics; bulk density (Bd), pH, cation exchange capacity (CEC), Calcium concentration (Ca), % composition of sand, % composition of clay, phosphorous (P) concentration, potassium (K) concentration, and magnesium (Mg) with transpiration (E) and net photosynthesis (Pn) for June, July, and August across all locations and species

	June				July				August			
	E		Pn		E		Pn		E		Pn	
Bd	-0.13	*	-0.08	NS	-0.11	NS	-0.16	**	-0.02	NS	-0.17	**
pH	-0.45	***	-0.39	***	-0.10	NS	0.02	NS	-0.06	NS	-0.21	**
CEC	-0.56	***	-0.45	***	-0.13	*	0.06	NS	-0.08	NS	-0.23	**
Ca	-0.52	***	-0.40	***	-0.08	NS	0.05	NS	-0.09	NS	-0.25	***
clay	0.54	***	0.34	***	0.14	*	0.00	NS	0.10	NS	0.20	**
sand	-0.50	***	-0.34	***	-0.17	**	0.00	NS	-0.09	NS	-0.15	*
P	0.20	***	0.22	**	0.17	**	0.13	*	0.07	NS	0.15	*
K	-0.46	***	-0.51	***	-0.12	*	0.23	***	-0.16	**	0.03	NS
Mg	-0.13	*	-0.34	***	-0.21	**	0.04	NS	-0.18	NS	0.10	NS

*,**,*** represent significance of p-values 0.05, 0.01, and <0.0001 respectively

Table 2-3. F-values for the influence of size on pre-dawn moisture potentials in June, July, and August of 2007 at the Lansing, MI locations

Species	June		July		August	
Acer x *freemanii* 'Autumn Blaze'	0.46	NS	2.66	*	5.31	**
Quercus bicolor	0.83	NS	2.16	NS	20.86	***
Platanus x *acerfolia* 'Bloodgood'	0.31	NS	2.12	NS	2.29	NS

*,**,*** represent significance of p-values 0.05, 0.01, and <0.0001 respectively
Sample size (n=2) in June and July and (n=5) in August

Table 2-4. Mean of pre-dawn moisture potential (ψ) of *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' in Lansing, MI from 7/4 to 8/17

Species	Size	4-Jul				24-Jul				8/15 - 8/17			
		ψ (-bars)				ψ (-bars)				ψ (-bars)			
Acer x *freemanii* 'Autumn Blaze'		n=2				n=2				N=5			
	1.75" BR	5.3	±	0.3	NS	7.5	±	0.6	NS	8.3	±	0.3	ab[x]
	1.75" B&B	4.9	±	0.7	NS	7.5	±	0.5	NS	7.4	±	0.4	abc
	2" B&B	5.3	±	0.3	NS	9.2	±	1.2	NS	7.1	±	0.4	bc
	2.5" B&B	5.2	±	0.5	NS	10.7	±	1.1	NS	6.9	±	0.3	c
	3" B&B	4.6	±	0.2	NS	9.3	±	0.6	NS	8.8	±	0.4	a
Quercus bicolor													
	1.75" BR	5.4	±	0.4	NS	10.2	±	1.3	NS	10.3	±	1.0	d
	1.75" B&B	5.4	±	0.4	NS	15.8	±	2.3	NS	11.5	±	0.8	c
	2" B&B	4.7	±	0.4	NS	13.4	±	1.0	NS	15.9	±	0.8	b
	2.5" B&B	5.4	±	0.7	NS	14.5	±	1.0	NS	19.2	±	0.9	a
	3" B&B	6.1	±	0.8	NS	13.0	±	1.4	NS	11.1	±	0.6	cd
Platanus x *acerfolia* 'Bloodgood'													
	1.75" BR	4.9	±	0.3	NS	7.8	±	0.7	NS	5.2	±	0.3	NS
	1.75" B&B	5.3	±	0.7	NS	8.8	±	1.0	NS	7.0	±	0.7	NS
	2" B&B	4.7	±	0.3	NS	7.9	±	1.1	NS	6.6	±	0.5	NS
	2.5" B&B	4.9	±	0.4	NS	8.4	±	1.3	NS	5.5	±	0.5	NS
	3" B&B	5.1	±	0.4	NS	11.4	±	1.0	NS	6.8	±	0.5	NS

size classes are indicated as BR for bare-root and B&B for balled-and-burlapped

[x] means within a column followed by the same letter are not different at $\alpha=0.05$

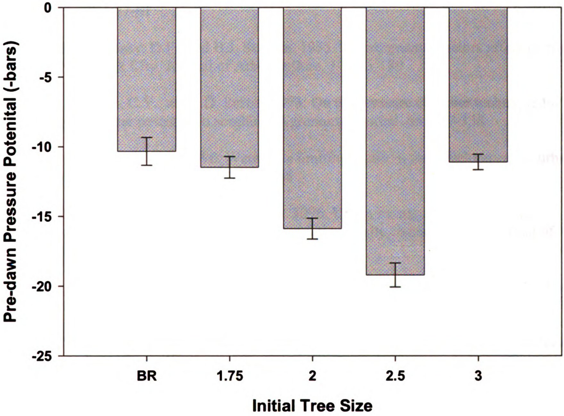

Figure 2-1. Influence of initial tree size on pre-dawn moisture potential (-bars) of five sizes of *Quercus bicolor* on 17 August 2007 in Lansing, MI

BR represents the 4.4 cm (1.75 in) size class

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APPENDIX

Table A-1. F-values of cumulative survival percentages of *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' during first two years of establishment in four Michigan Communities

	Acer x *freemanii* 'Autumn Blaze'			*Quercus bicolor*			*Platanus* x *acerfolia* 'Bloodgood'		
Effect	DF	F-value	P-value	DF	F-value	P-value	DF	F-value	P-value
S	4	0.30	NS	4	0.39	NS	4	2.24	NS
L	4	1.16	NS	4	0.93	NS	3	2.98	*
Y	2	0.53	NS	2	5.52	*	2	1.92	NS
S x L	16	0.51	NS	16	0.80	NS	12	1.45	NS
S x Y	8	0.40	NS	8	0.94	NS	8	0.93	NS
L x Y	8	0.93	NS	8	0.54	NS	6	1.63	NS
S x L x Y	32	0.70	NS	32	0.71	NS	24	0.82	NS

Size (S) refers to intial stock size, location (L) represents location of research plot, and year (Y) refers to data collected in October 2006, October 2007, and June 2008

Table A-2. F-values of the visual assessment rating of *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' during first two years of establishment in four Michigan Communities

Effect	*Acer* x *freemanii* 'Autumn Blaze'		*Quercus bicolor*		*Platanus* x *acerfolia* 'Bloodgood'	
S	0.70	NS	15.09	***	12.58	***
L	13.41	***	8.32	***	42.11	***
Y	0.31	NS	4.60	*	0.24	NS
S x L	1.32	NS	1.86	*	3.23	**
S x Y	0.31	NS	0.26	NS	1.09	NS
L x Y	1.10	NS	4.99	**	1.97	NS
S x L xY	0.51	NS	1.43	NS	0.81	NS

Size (S) refers to initial stock size, location (L) refers to the location of research plot, and year (Y) refers to data collected in June of 2007 and 2008

*,**,*** $p \leq 0.05, 0.01.0.0001$ respectively

Table A-3. F-values of relative growth rate of *Acer x freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' during first two years of establishment in four Michigan communities

Effect	Maples		Oaks		Planes	
	2006	2007	2006	2007	2006	2007
S	10.40 ***	7.81 ***	1.87 NS	2.67 *	8.89 ***	15.85 ***
L	6.36 **	8.90 ***	2.21 NS	1.84 NS	5.59 **	18.91 ***
S x L	2.14 *	1.13 NS	1.97 *	0.87 NS	1.34 NS	1.55 NS

Size (S) refers to intial stock size and location (L) refers to the location of research plot

*,**,*** p ≤ 0.05, 0.01.0.0001 respectively

Table A-4. F-values of canopy volume of *Acer x freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' during first two years of establishment in four Michigan communities

Effect	*Acer* x *freemanii* 'Autumn Blaze'			*Quercus bicolor*			*Platanus* x *acerfolia* 'Bloodgood'		
	Baseline	2006	2007	Baseline	2006	2007	Baseline	2006	2007
S	48.72 ***	110.35 ***	44.23 ***	87.68 ***	90.22 ***	5.89 **	118.43 ***	136.55 ***	38.73 ***
L	1.16 NS	2.26 NS	24.91 ***	3.61 **	3.67 **	1.42 NS	4.27 **	5.98 **	26.30 ***
S x L	2.47 **	2.15 *	1.90 *	3.95 ***	3.60 ***	0.97 NS	2.60 **	2.75 **	1.41 NS

Size (S) refers to initial stock size and location (L) refers to the location of research plot.

Baseline measurements acquired in May 2006

*,**,*** p ≤ 0.05, 0.01.0.0001 respectively

Table A-5. F-values of individual leaf area of *Acer x freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' during first two years of establishment in four Michigan communities

Effect	*Acer* x *freemanii* 'Autumn Blaze'			*Quercus bicolor*			*Platanus* x *acerfolia* 'Bloodgood'		
	Baseline	2006	2007	Baseline	2006	2007	Baseline	2006	2007
S	1.56 NS	1.35 NS	5.52 **	14.70 ***	1.41 NS	6.35 **	75.35 ***	47.60 ***	6.91 ***
L	7.97 ***	2.38 NS	11.34 ***	2.14 NS	0.61 NS	0.94 NS	6.73 **	54.25 ***	5.68 **
S x L	1.29 NS	1.40 NS	0.97 NS	1.67 NS	1.68 NS	0.57 NS	4.87 ***	12.58 ***	0.74 NS

Size (S) refers to initial stock size and location (L) refers to the location of research plot.

Baseline measurements acquired in May 2006

*,**,*** $p \leq 0.05, 0.01.0.0001$ respectively

Table A-6. F-values of light interception of *Acer x freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' in four Michigan communities during June, July, and August 2007

Effect	*Acer* x *freemanii* 'Autumn Blaze'			*Quercus bicolor*			*Platanus* x *acerfolia* 'Bloodgood'		
	June	July	August	June	July	August	June	July	August
S	10.23 ***	7.42 ***	5.26 **	3.50 *	3.48 *	10.23 ***	5.49 **	4.02 **	0.83 NS
L	16.39 ***	6.95 ***	3.82 **	2.61 *	3.29 *	16.39 ***	23.67 ***	9.32 ***	23.42 ***
S x L	0.58 NS	0.67 NS	2.36 **	0.98 NS	0.88 NS	0.58 NS	1.05 NS	0.71 NS	1.15 NS

Size (S) refers to initial stock size and location (L) refers to the location of research plot.

Baseline measurements acquired in May 2006

*,**,*** $p \leq 0.05, 0.01.0.0001$ respectively

Table A-7. F-values of shoot elongation of *Acer* x *freemanii* 'Autumn Blaze', *Quercus bicolor*, and *Platanus* x *acerfolia* 'Bloodgood' during first two years of establishment in four Michigan communities

Effect	*Acer* x *freemanii* 'Autumn Blaze'		*Quercus bicolor*		*Platanus* x *acerfolia* 'Bloodgood'	
	2006	2007	2006	2007	2006	2007
S	8.9 ***	3.8 **	11.0 ***	1.2 NS	24.0 ***	4.9 **
L	7.4 ***	10.8 ***	3.1 *	5.8 **	16.7 ***	15.3 ***
S x L	2.9 **	1.0 NS	1.1 NS	1.0 NS	1.4 NS	0.5 NS

Size (S) refers to initial stock size and location (L) refers to the location of research plot.

*,**,*** $p \leq 0.05, 0.01.0.0001$ respectively

Table A-8. Pearson correlation coefficients of visual assessment ratings in relation to relative growth rate (RGR), light interception (LI), leaf area (LA), branch growth (BG), and cumulative survival percentage (SURV) from April 2006 to June 2008

	Visual Assessment Rating			
	2007		2008	
RGR1	0.15	*	0.11	NS
RGR2	0.41	***	0.37	***
LIJUN	0.52	***	0.41	***
LIJUL	0.41	***	0.41	***
LIAUG	0.32	***	0.31	***
LA06	-0.01	NS	0.03	NS
LA07	-0.12	*	0.02	NS
LA08	0.14	*	0.11	NS
BG06	0.13	*	0.08	NS
BG07	0.32	***	0.26	***
SURV06	0.37	***	.	
SURV07	0.36	***	.	
SURV08	0.45	***	0.26	***
VR	.		0.58	***

*,**,*** $p \leq 0.05$, 0.01.0.0001 respectively

Table A-9. Pearson correlation of soil characteristics bulk density (Bd), pH, cation exchange capacity (CEC), textural composition (% sand, silt, and clay), concentration of calcium (Ca), phosphorous (P), potassium (K), magnesium (Mg), and visual assessment ratings (VR) with monthly stomatal conductance (Gs) and net photosynthesis (Pn) of *Acer* x *freemanii* 'Autumn Blaze'. during June, July, and August 2007

	Gs_{June}	Pn_{June}	Gs_{July}	Pn_{July}	Gs_{August}	Pn_{August}
Bd	-0.09 NS	-0.10 NS	-0.20 NS	-0.20 NS	0.09 NS	0.20 NS
pH	-0.41 ***	-0.50 ***	-0.20 *	-0.30 **	0.00 NS	-0.10 NS
CEC	-0.69 ***	-0.60 ***	-0.30 **	-0.40 **	-0.20 NS	-0.20 *
Sand	-0.22 *	-0.20 *	0.00 NS	0.00 NS	-0.30 **	-0.20 NS
Silt	-0.27 **	-0.30 **	-0.10 NS	-0.10 NS	-0.20 NS	-0.10 NS
Clay	0.27 **	0.29 **	0.07 NS	0.08 NS	0.27 *	0.18 NS
Ca	-0.53 ***	-0.50 ***	-0.30 **	-0.30 **	-0.10 NS	-0.20 NS
P	-0.21 *	-0.10 NS	0.09 NS	0.05 NS	-0.20 NS	-0.30 **
K	-0.67 ***	-0.70 ***	-0.10 NS	-0.20 NS	-0.30 *	-0.30 **
Mg	0.03 NS	-0.20 *	0.18 NS	0.12 NS	-0.10 NS	-0.10 NS
VR_{2007}	-0.13 NS	-0.20 NS	0.27 **	0.16 NS	-0.10 NS	-0.10 NS
VR_{2008}	-0.01 NS	0.03 NS	0.31 **	0.35 **	-0.20 NS	-0.30 **

*,**,*** $p \leq 0.05$, 0.01.0.0001 respectively

Table A-10. Pearson correlation of soil characteristics bulk density (Bd), pH, cation exchange capacity (CEC), textural composition (% sand, silt, and clay), concentration of calcium (Ca), phosphorous (P), potassium (K), magnesium (Mg), and visual assessment ratings (VR) with monthly stomatal conductance (Gs) and net photosynthesis (Pn) of *Quercus bicolor*. during June, July, and August 2007

	Gs_{June}		Pn_{June}		Gs_{July}		Pn_{July}		Gs_{August}		Pn_{August}	
Bd	-0.30	**	-0.30	**	-0.30	*	-0.30	**	-0.50	***	-0.50	***
pH	-0.60	***	-0.50	***	0.16	NS	0.08	NS	-0.30	**	-0.40	**
CEC	-0.60	***	-0.50	***	0.21	NS	0.15	NS	-0.30	*	-0.30	**
Sand	-0.50	***	-0.40	**	0.09	NS	0.11	NS	-0.20	NS	-0.20	NS
Silt	-0.50	***	-0.30	**	0.16	NS	0.14	NS	-0.30	*	-0.30	**
Clay	0.52	***	0.36	**	-0.10	NS	-0.10	NS	0.22	*	0.24	*
Ca	-0.60	***	-0.50	***	0.20	NS	0.13	NS	-0.30	**	-0.40	**
P	0.28	**	0.36	**	0.06	NS	0.01	NS	0.25	*	0.26	*
K	-0.50	***	-0.40	**	0.32	**	0.41	***	0.28	*	0.22	*
Mg	-0.20	NS	-0.20	*	0.14	NS	0.19	NS	0.19	NS	0.20	NS
VR_{2007}	0.06	NS	0.03	NS	0.14	NS	0.12	NS	0.26	*	0.29	**
VR_{2008}	0.24	*	0.28	**	0.42	**	0.37	**	0.49	***	0.43	***

*,**,*** $p \leq 0.05, 0.01.0.0001$ respectively

Table A-11. Pearson correlation of soil characteristics bulk density (Bd), pH, cation exchange capacity (CEC), textural composition (% sand, silt, and clay), concentration of calcium (Ca), phosphorous (P), potassium (K), magnesium (Mg), and visual assessment ratings (VR) with monthly stomatal conductance (Gs) and net photosynthesis (Pn) of *Platanus* x *acerfolia* 'Bloodgood' during June, July, and August 2007

	Gs_{June}	Pn_{June}	Gs_{July}	Pn_{July}	Gs_{August}	Pn_{August}
Bd	0.20 NS	0.30 **	-0.10 NS	-0.10 NS	-0.10 NS	-0.10 NS
pH	-0.30 **	-0.10 NS	0.04 NS	0.27 **	0.00 NS	-0.10 NS
CEC	-0.50 ***	-0.30 **	0.13 NS	0.34 **	-0.10 NS	-0.20 NS
Sand	0.31 **	0.20 *	-0.10 NS	-0.20 NS	0.03 NS	-0.10 NS
Silt	-0.30 **	-0.30 **	0.02 NS	0.08 NS	-0.10 NS	0.08 NS
Clay	-0.20 *	0.00 NS	0.12 NS	0.24 *	0.03 NS	0.00 NS
Ca	-0.40 **	-0.10 NS	0.15 NS	0.36 **	-0.10 NS	-0.20 NS
P	-0.10 NS	-0.10 NS	-0.10 NS	-0.10 NS	-0.10 NS	0.04 NS
K	-0.70 ***	-0.70 ***	0.10 NS	0.35 **	-0.10 NS	0.05 NS
Mg	-0.30 **	-0.60 ***	-0.20 *	-0.10 NS	-0.10 NS	0.13 NS
VR_{2007}	0.00 NS	-0.10 NS	0.00 NS	-0.10 NS	0.00 NS	0.00 NS
VR_{2008}	0.18 NS	0.07 NS	0.00 NS	-0.10 NS	0.10 NS	0.07 NS

*,**,*** $p \leq 0.05$, 0.01.0.0001 respectively

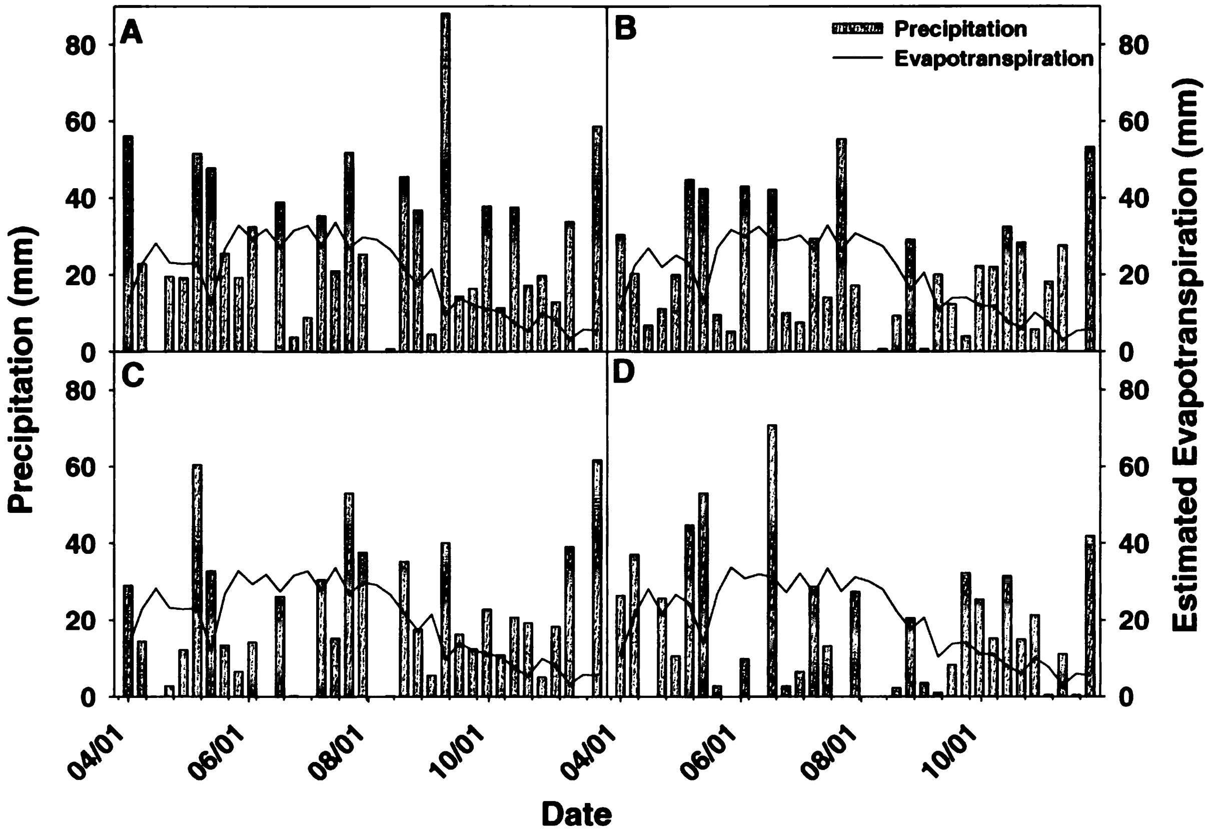

Figure A-1. Rainfall deficit, precipitation, and estimated evapotranspiration of (A) Ann Arbor, (B) Detroit, (C) Lansing, and (D) Rochester Hills, MI from 4/1/2006 to 10/31/2006

Estimated evapotranspirational loss data collected from the Michigan Agricultural Weather Network
Rochester Hills precipitation data is average of reported precipitation in Pontiac and Shelby Township, MI
Estimated evapotranspirational water loss for Detroit is mean of Lapeer and Dundee, MI agricultural centers