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The Environmental Benefits of Trees on an Urban University Campus

Corinne G. Bassett
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Abstract
The University of Pennsylvania is situated on a rapidly growing and highly urbanized campus that, as of the summer of 2015, contained over 6,000 trees. Trees play an important ecological role within the urban environment, as well as support improved public health and provide aesthetic benefits to cities (Nowak et al. 2008; McPherson et al., 2003). This capstone project used the United States Department of Agriculture Forest Service's software, i-Tree Eco, to quantify the ecosystem benefits that the University of Pennsylvania urban forest conveys to its community. Field research teams collected data on location and tree canopy size for 4,086 trees on 160 acres in the core of the Philadelphia campus during the summer of 2015. Trees within the Core Campus were estimated to store a total of 1,576,717 lbs of carbon and prevented $51,871 in building heating/cooling energy costs. This project will give Penn Facilities and Real Estate Services decision makers a more complete assessment of the value of their urban trees. This work will inform future tree management practices and create a precedent for ongoing urban forestry research efforts at Penn.

Disciplines
Environmental Indicators and Impact Assessment | Environmental Sciences | Natural Resource Economics | Natural Resources and Conservation | Natural Resources Management and Policy | Other Environmental Sciences | Other Forestry and Forest Sciences | Physical Sciences and Mathematics | Urban, Community and Regional Planning

THE ENVIRONMENTAL BENEFITS OF TREES ON AN URBAN UNIVERSITY CAMPUS

Corinne G. Bassett

Master of Environmental Studies
Environmental Biology

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Sally Willig, Ph.D., University of Pennsylvania

ABSTRACT

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Jason Henning, Ph.D.

The University of Pennsylvania is situated on a rapidly growing and highly urbanized campus that, as of the summer of 2015, contained over 6,000 trees. Trees play an important ecological role within the urban environment, as well as support improved public health and provide aesthetic benefits to cities (Nowak et al. 2008; McPherson et al., 2003). This capstone project used the United States Department of Agriculture Forest Service's software, i-Tree Eco, to quantify the ecosystem benefits that the University of Pennsylvania urban forest conveys to its community. Field research teams collected data on location and tree canopy size for 4,086 trees on 160 acres in the core of the Philadelphia campus during the summer of 2015. Trees within the Core Campus were estimated to store a total of 1,576,717 lbs of carbon and prevented $51,871 in building heating/cooling energy costs. This project will give Penn Facilities and Real Estate Services decision makers a more complete assessment of the value of their urban trees. This work will inform future tree management practices and create a precedent for ongoing urban forestry research efforts at Penn.

Acknowledgements

This capstone would not have been possible without the team of supporters that helped me each step of the way:

First and foremost, many thanks go to Jason Henning for responding to every single question I had with perspective and reassurance and for his expert guidance for the entire journey. Thank you to Sally Willig for advising me on this project and inspiring me at each stage of my academic career that led me to this capstone.

I would like to thank Robert Lundgren and Chloe Cerwinka for their unbelievable support and for inviting me to be a part of realizing their beautiful vision for the Penn campus. I also could not have been luckier to have Jenny Lauer and Trish Kemper as my partners through the seemingly endless, hot, Philadelphia summer days of field work. Their unfailing optimism, perseverance, and dedication to measuring every last tree made this project possible. Another big thank you to Lara Roman and Jason Fristensky for their technical expertise and help to get this project started from the beginning.

Lastly, I thank the urban forestry and arboriculture staff at the Morris Arboretum for giving their time and effort to this project. Thank you to Andrew Hawkes and Joshua Best for lending a hand in the final "tree measuring blitz week" it took to complete the field work. Thank you to Jason Lubar and Bob Wells for giving me the urban forestry foundation that inspired me to undertake this project in the first place.

Table of Contents

List of Tables

List of Figures

Introduction

The environmental benefits of trees in urban landscapes are numerous and well established in urban forestry literature. Urban trees improve air quality, cool local air temperatures, filter and retain storm water, sequester carbon, and contribute to healthier and more beautiful cities (Nowak et al. 2002; Nowak et al. 2008; McPherson et al. 2003).

In addition to providing clear benefits to humans, trees provide essential habitat and food sources for wildlife in a landscape increasingly fragmented by urban development. Even small urban parks provide significant habitat for local and migrating birds (Rega et al. 2015). Trees on streets and in parks are now recognized as more than just pleasant features with associated maintenance costs; they are the backbone of urban forests and ecosystems.

The concentration of impervious surfaces and building mass in cities creates health and safety problems for both infrastructure and residents to include the urban heat island effect and stormwater runoff surges (Susca, et al. 2011). Researchers and public officials are increasingly calling for the implementation of green infrastructure within cities, including tree planting campaigns, to help mitigate the environmental effects of urbanization (Young 2013).

People living and working near trees and parks experience a host of positive health and living standard benefits such as relief from environmental stresses of cities caused by factors like population density and air pollution. Trees can improve the mental health of communities and relieve stress. Exposure to nature and restorative environments increases sustained attentional capacity (Berto 2005). Easy access to green outdoor environments from workplaces has been found to significantly reduce worker stress (Lottrup 2013). Overall, academic institutions and hospitals have found that natural settings and trees result in measurably positive impacts on students and patients (Wolf et al. 2014).

The benefits of urban trees are not only well recognized by the academic community, but by municipalities and institutions around the country and the world (Seamans 2013). City "greening campaigns" like MillionTrees NYC and the UK Big Tree Plant are evidence of both governmental and public support for increased urban canopy ("MillionTrees NYC," 2015; "Forestry Commission England," 2015). Philadelphia's own Plant One Million campaign has also garnered community support and progress, surpassing 500,000 trees planted in 2015 ("Plant One Million Trees," 2015). However, even when general benefits of urban trees are understood and desired, it is difficult to manage and maximize their benefits without quantitative information on the direct benefits of an urban forest (Nowak et al. 2007).

The benefits of trees can vary widely depending on the context in which they are planted (Hale et al. 2015). For example, planting trees strategically near buildings can maximize the impact of trees' cooling effect and subsequently reduce air conditioning costs. Planting large species of trees and maintaining them so they reach maturity results in more benefits than the same number of trees of a smaller species (Sydnor et al. 2011). Simply planting trees without consideration for their species, location, and maintenance will not result in all of their wished-for benefits. It is essential to plan where trees are planted and to plan their ongoing maintenance in order to maximize future benefits and to ensure long-term tree survival and growth.

Trees at Penn

The over 6,000 trees on Penn's University City campus are managed by the University Landscape Architect, Robert Lundgren, and the Landscape Planner, Chloe Cerwinka. The University of Pennsylvania has had many successes in managing its landscape; the towering heritage zelkovas and London planetrees lining Locust Walk, or the elms, ashes, and oaks shading College Green, shape and define an iconic campus. These trees were planted and maintained over the last 150 years and are a legacy of the campus's history and growth.

Penn has also demonstrated its commitment to urban tree cover on campus and within Philadelphia through its "Creating Canopy" tree giveaway program, its strengthened connection with the Morris Arboretum in Chestnut Hill, its recognition as a Tree Campus USA for six years running, and the inclusion of many tree related initiatives in Penn's Climate Action Plan 2.0 (University of Pennsylvania 2014).

Figure 1: Parallel and adjacent streets, Walnut Street (left) and Locust Walk (right), offer two examples of extremes in tree cover (Carney, 2015, University of Pennsylvania, 2015).

However, Penn's well known "treed spaces" are only part of the overall picture of Penn's urban forest and not representative of every space on campus. On a hot summer day, walking along the tree-lined shade of Locust Walk is a much cooler and more pleasant experience than walking through the concrete corridor of Walnut Street (Figure 1). Both streets are important arteries in the heart of campus, trafficked daily by students, faculty, staff and guests, yet images of Walnut Street are almost never included in University marketing materials (University of Pennsylvania, 2015).

Despite their known environmental, human health, and aesthetic benefits, trees on urban campuses like Penn's face threats from the dense urban environment in which they live, including disease, unsatisfactory soil conditions, vandalism, and pollution. In rapidly changing neighborhoods like University City, trees are often removed or fatally damaged when they are located near new construction projects. Maintaining the campus tree resource requires significant effort by university planners to organize maintenance schedules around a sound campus tree policy and secure funds for new tree planting and arboricultural services. University planning decisions that maximize the effect of university tree resources will result in a cooler, healthier, and more pleasant environment.

The University of Pennsylvania Climate Action Plan was first written and implemented in 2009, with an aspirational goal of working towards carbon neutrality by year 2042. The plan contains goals for reducing carbon emissions and energy consumption University wide, in addition to separate sustainability goals for various divisions throughout the University. The five-year progress review and update completed in fiscal year 2014 found that Penn had reduced its carbon emissions by 18% and normalized energy consumption by 6.6% since the fiscal year 2007 baseline. There are plans already in place through the Climate Action Plan 2.0 to increase green spaces and revise Penn's landscape practices (University of Pennsylvania 2014). Linking the beneficial effects of trees with Penn's sustainability goals could expand the institutional recognition of the value of trees beyond their aesthetic worth to the human and environmental advantages they provide.

Quantifying the values of trees at Penn is an important step towards further incorporating trees into University-wide planning. There are currently several United States Forest Service research projects underway studying the tree canopy change at Penn. This study is part of a greater effort to understand Penn's urban forest and guide its future direction.

i-Tree Eco

i-Tree Eco is part of a suite of software (Version 5.1.13, i-Tree Tools, 2015) developed by the United States Department of Agriculture Forest Service to assess and analyze urban forest benefits and structure. It has been used widely by municipalities and institutions to assess the ecosystem services trees provide a community (Martin et al. 2011; City of Providence 2014).

i-Tree Eco produces estimates of the amount and monetary value of the benefits of trees related to storm water mitigation, air quality, carbon sequestration, and energy savings from reduced heating and cooling. Benefits estimates are derived from an inventory based on field measurements of trees. i-Tree Eco merges collected data on tree and canopy size with local hourly weather and pollution concentration data to produce summary reports (i-Tree Tools 2015).

Though the over 6000 trees on Penn's campus trees do have many identifiable environmental benefits, the amount and type of benefits they provide is unknown without further study. The purpose of the i-Tree Eco assessment is to provide a more complete picture of the current status and value of Penn's campus forest. The results of this assessment will substantiate ongoing tree management practices and provide quantitative data to guide future tree-related priorities. Using this peer-reviewed software to quantify the benefits of trees on campus not only captures the legacy of a historic campus landscape, but is part of a University-wide commitment to research and sustainability.

Methods

Field data was collected on 4,086 trees between June 23rd and August 31st, 2015. Data collectors were four past or present Morris Arboretum interns, trained in i-Tree Eco collection protocol by Jason Henning of the U.S. Forest Service Philadelphia Field Station. Corinne Bassett collected data for four days a week in teams with Jennifer Lauer and Trish Kemper, each for two days a week. Andrew Hawkes, the Morris Arboretum Assistant Arborist, and Joshua Best, the 2015 Morris Arboretum Arborist Intern, also helped with fieldwork for four days. In total, 49 days of pair work occurred. Given eight hours of fieldwork per day, approximately 784 person hours were required to complete the field data collection. An additional approximate 200 person hours were spent preparing the data to be processed with i-Tree Eco Version 5.1.13 (half of this time was spent entering and mapping new trees in the Penn database) and analyzing the results.

The Penn i-Tree Eco inventory was conducted in accordance with the procedures outlined in i-Tree Eco User's Manual v. 5.0, developed by the U.S. Forest Service, Northeast Research Station. It was conducted as a complete inventory project where 100% of trees in a given area are inventoried (i-Tree Tools, 2015). Data management and storage procedures were designed to fit with current practices at Penn and to increase the usability of the data collected and the ability to re-measure trees in the future to determine growth and patterns of change.

All trees in this study met a minimum requirement of being woody plants over 6ft in height and over 1" in diameter at breast height (DBH, 4.5 feet above ground). This standard included many large woody plants often considered to be shrubs, like *Viburnum prunifolium* (blackhaw viburnum) and *Hamamelis virginiana* (common witchhazel). Consequently, 808 trees were added to the existing Penn tree database as a result of this project because they met the i-Tree Eco size standard for trees, but had not previously been formally mapped or logged.

Trees were identified to the species and cultivar level where possible, and to the genus at minimum. Most trees were previously identified in the existing Penn database, though the 808 newly inventoried trees were identified by field crews. Before i-Tree Eco processing, species listed in the database were matched with their corresponding i-Tree Eco species code. In cases where planted cultivars did not have defined i-Tree Eco species codes, they were listed as the straight species. For example, *Ulmus americana* 'Princeton,' was given the same code as *Ulmus americana*, and *Gleditsia triacanthos* var. *inermis* was given the same code as *Gleditsia triacanthos*.

Project site

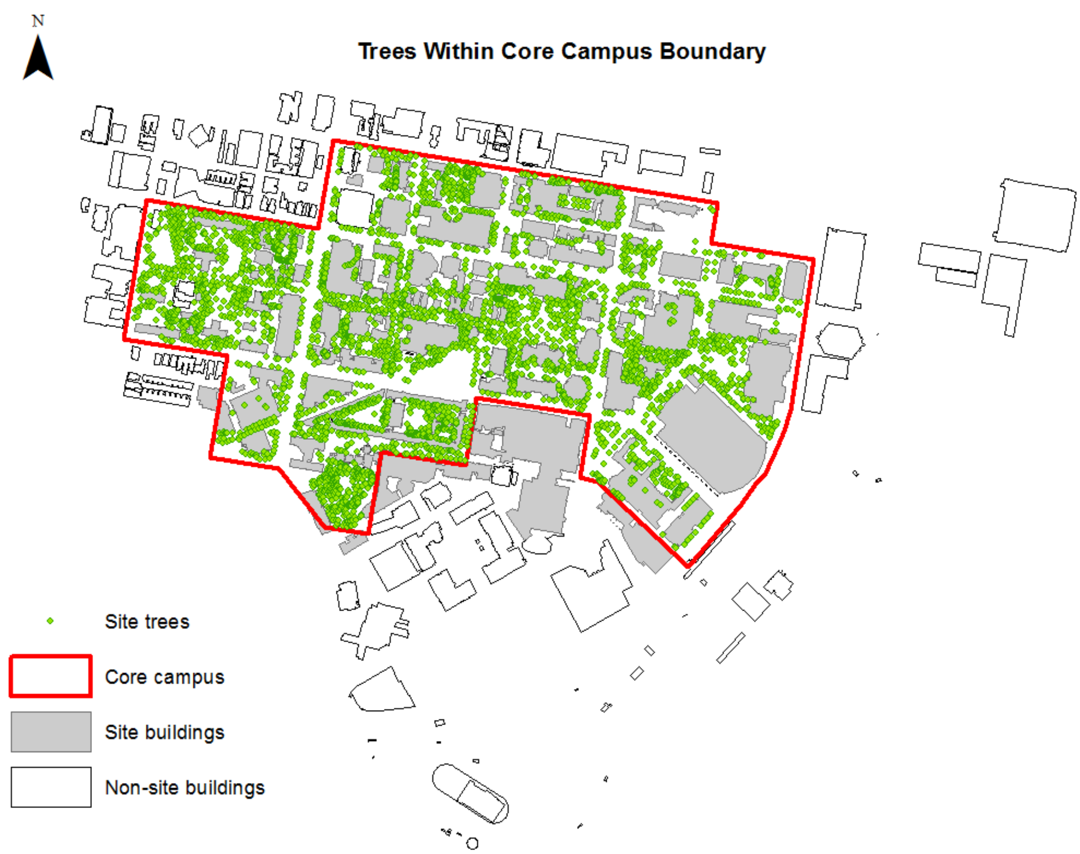

Figure 2: Core Campus boundary used in USDA Forest Service study and i-Tree Eco study.

A USDA Forest Service Philadelphia Field Station team led by Lara Roman, Ph.D., recently completed a study on canopy change at Penn over time. Their work defined a 160-acre core study area on Penn's University City campus (Figure 2). The i-Tree Eco assessment was conducted using the same study area boundaries to allow for comparison between the two projects now, and into the future. It encompasses both the central area of the University City campus and areas managed directly by the University Landscape Architect, Robert Lundgren.

Data management

Penn maintains a database and map of its plants using BG-Base (Version 7.0., Walter et al. 2012) and BG-Map (Version 2015b, Glicksman 2015) a suite of specialized botanic garden management software used by arboreta, botanic gardens, and academic institutions around the world. BG-Base is the database management program, and in this system, all trees on campus have a unique identifier or "accession number". These accession numbers are a combination of the year the plant was added to the database, a sequential number, and a qualifying symbol. For example, the first plant accessioned in 2015 is 2015-0001*A, the next is 2015-0002*A (Figure 2). Data on the species, origin, health, and management history are recorded for each accessioned plant within BG-Base. All plants in the BG-Base inventory are mapped in BG-Map, an AutoCAD-based geographic information system, overlaid on the Penn campus plan.

Field data

Garden Notepad Plus is an iPad web application (Version 4.2.5, Glicksman 2015) that allows users to collect data on plants in the field, and upload the information to BG-Map. i-Tree Eco data was collected with Garden Notepad Plus 4.2.5 in an attempt to integrate the new data with Penn's existing plant management system. Penn worked with Mark Glicksman of BG-Map to add a specialized section for collecting i-Tree Eco data fields into Garden Notepad Plus. Various software issues were encountered which slowed the data collection process, but did not affect the end results of the project. Through testing this addition, the field crews worked with Mark Glicksman to make five total software updates: Garden Notepad Plus 4.2.1, Garden Notepad Plus 4.2.2, Garden Notepad Plus, 4.2.3, Garden Notepad Plus 4.2.4, and Garden Notepad Plus 4.2.5.

The variables collected were total height, height to live canopy top, height to canopy base, canopy width north-south, canopy width east-west, diameter at breast height (4.5 feet) for up to 6 stems, height of diameter measure, estimated percent canopy missing, estimated percent canopy dieback, crown light exposure, and street tree status (i-Tree Tools, 2015). i-Tree Eco also required a land use and status for each tree; for the Penn inventory, all trees were assigned a land use of "Institutional" and a status of "Planted." Using Garden Notepad Plus allowed for this Penn i-Tree Eco data to be cataloged by Penn accession numbers along with existing data.

Tree heights were measured using an Optilogic 100LH hypsometer and recorded to the nearest foot. Canopy widths were measured using a standard 100ft fabric measuring tape to the nearest foot. DBH was measured to the nearest $1/10^{th}$ inch using a fabric diameter tape from Forestry Suppliers. Stems were measured at a height of 4.5 feet for almost all trees. For trees with branching structures that prevented measuring at 4.5 feet, the height that diameter was measured at was recorded to the nearest tenth of a foot. For multi-stemmed trees, up to six stems were measured with only the six largest selected where there were more than six stems.

Derived data

Calculating energy savings in i-Tree Eco requires measuring the distance and direction from every tree greater than 20 feet tall to the three nearest buildings within 60 feet. Jason Fristensky, from the USDA Forest Service and a recent graduate of the Penn Masters of Landscape Architecture program, helped to design a method to calculate these distances and directions using the existing Penn tree map. The Penn tree map and building footprint AutoCAD layers, provided by the University of Pennsylvania Division of Facilities and Real Estate Services, were brought into ArcMap 10.3, and the distances and directions calculated by generating a Near Table (Figure 3).

Figure 3: Distances in feet from tree center points to building polygons, as measured using ArcGIS. Trees are labeled by accession number and species. This is a close up of the music building courtyard and engineering quad. (Google Maps, 2015).

Open air parking facilities were removed from the calculation because the energy savings calculations are only relevant to space conditioned structures. Some buildings within the Core Campus study boundary were not included because they are managed independently from the University of Pennsylvania, namely:

- The Wistar Institute
- The Free Library of Philadelphia
- St. Agatha and St. James' Church
- St. Mary's Church

The energy savings formulas in i-Tree Eco were created for residential buildings that are three stories or lower. Buildings on the University of Pennsylvania campus range in shape and size, but are mostly taller than three stories. Because of these restrictions, energy savings estimates may be less precise and are likely conservative. 67 trees on campus are on top of buildings, in rooftop meadows, or in courtyards above climate controlled floors. Though these trees convey a benefit to the buildings they are on, in an effort to be conservative, they were left out of energy calculations because their relative positioning did not fit within the i-Tree Eco model. The energy and heating prices used to calculate these benefits were the average rates for electricity and steam in 2015: 0.1284 $/kWh and 1.452 $/Therm (University of Pennsylvania Division of Facilities and Real Estate Services, 2015).

Results

Biodiversity and Forest Structure

There are 228 different tree species in the Penn Core Campus. The five most common trees in the study area were *Gleditsia triacanthos* (honeylocust), *Magnolia virginiana* (sweetbay magnolia), *Platanus x acerifolia* (London planetree), *Amelanchier sp.*(serviceberry), and *Zelkova serrata* (Japanese zelkova) (Figure 4). The top ten most abundant species make up 37.3% of the trees in the Core Campus.

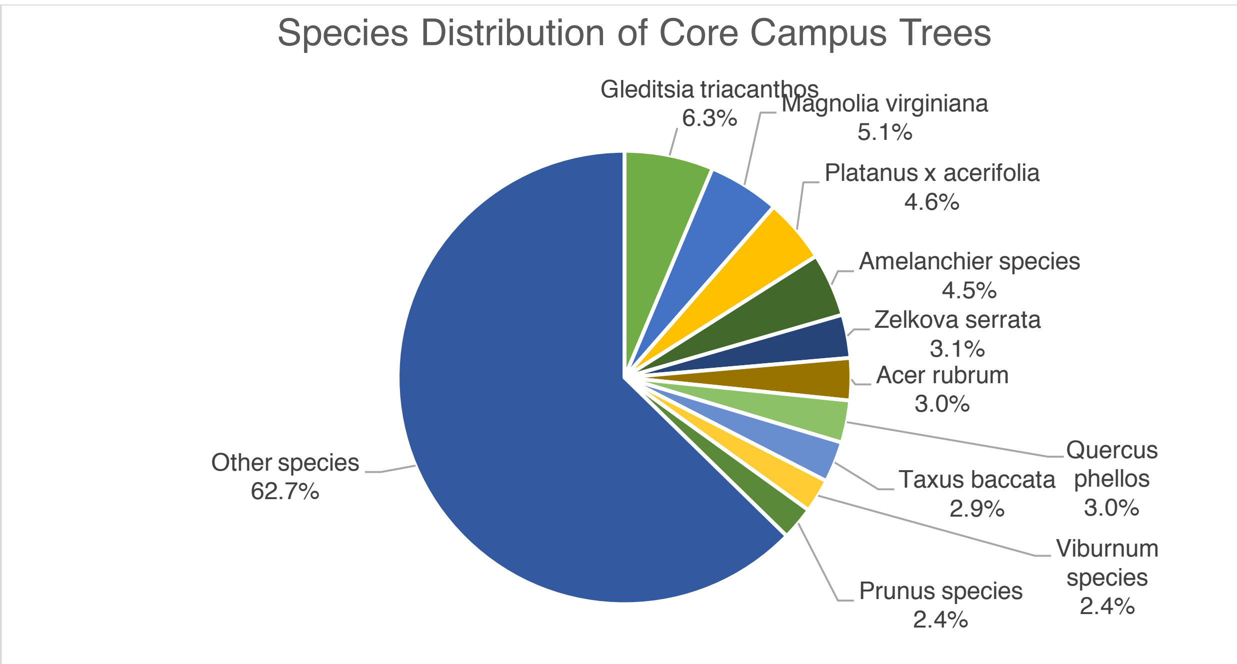

Figure 4: Relative abundance of tree species in the University of Pennsylvania Core Campus.

Looking at the top ten most prevalent species in order of other variables yields a different picture of which types of trees make up the population at Penn. While there are many measurements that capture the size of a tree, diameter at breast height (DBH) is a measurement commonly used as a proxy for tree size and age. Studying the distribution of DBHs within a population indicates the population's structure at present and the trajectory of the population's structure in the future. Most of the trees in the Core Campus were between 1-6 inch DBH. The median DBHs and structural values of shadetrees with average heights greater than 40 feet are much lower than their average DBHs and structural values, demonstrating how a few large trees heavily influence the total benefits of an inventory (Table 1).

	% of All Trees	Avg. DBH (in)	Median DBH (in)	Avg. Height (ft)	Median Height (ft)	Avg. Structural Tree Value ($)	Median Structural Value ($)
Gleditsia triacanthos	6.34	8.6	7.3	41	36	998	742
Magnolia virginiana	5.09	3.8	3.6	18	16	382	342
Platanus x acerifolia	4.58	17.5	15.5	60	61	3531	2316
Amelanchier species	4.53	3.6	3.2	15	14	315	218
Zelkova serrata	3.08	13.1	9.9	40	35	2718	1237
Acer rubrum	3.01	9.5	8.4	44	42	1307	969
Quercus phellos	3.01	11.0	9.9	44	41	1889	1243
Taxus baccata	2.91	5.0	4.5	14	14	543	527
Viburnum species	2.40	2.9	2.6	10	9	220	141.5
Prunus species	2.37	8.2	7.7	25	23	819	712
All Trees	100	8.1	5.7	31	24	1217	609

Table 1: Average and median values for characteristics of each of the top ten most abundant species on campus. Trees shaded in light blue have ≥40ft average heights and represent large shadetrees.

The four most abundant native shadetrees, *Gleditsia tricanthos* (honeylocust), *Platanus x acerifolia* (London planetree), *Quercus phellos* (willow oak), and *Acer rubrum* (red maple), illustrate some of the possible variance of DBH size class distributions within their populations (Figures 5-9). For each of these four species, there were relatively small percentages of 1-3 inch DBH trees, indicating that small trees of these species have not been planted in proportion to each species population. In particular, the relatively wide distribution of London planetrees and the low number of trees in smaller diameter classes shows that as these large, mature, trees age and eventually have to be removed, there will not be enough intermediate and small trees to replace them and their benefits (Figures 5 through 9). The unique role that London planetrees fill in providing ecosystem services cannot be sustained with the current amount of younger trees.

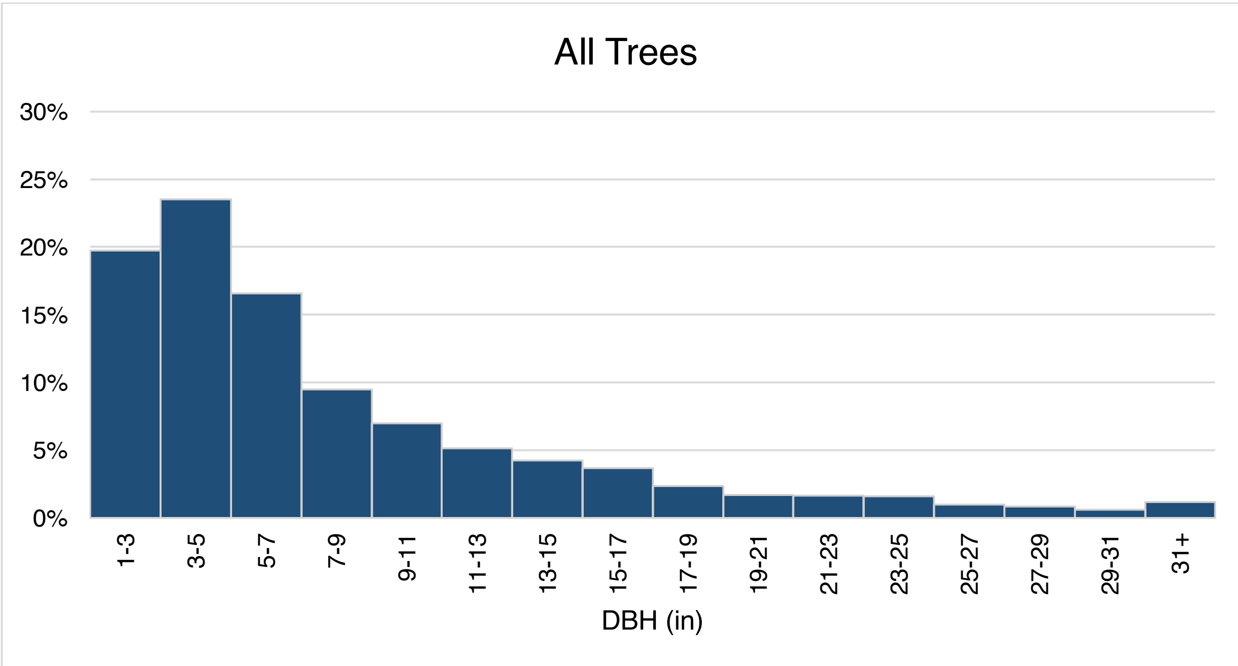

Figure 5: Percentage of trees within DBH size classes of all trees in the Core Campus.

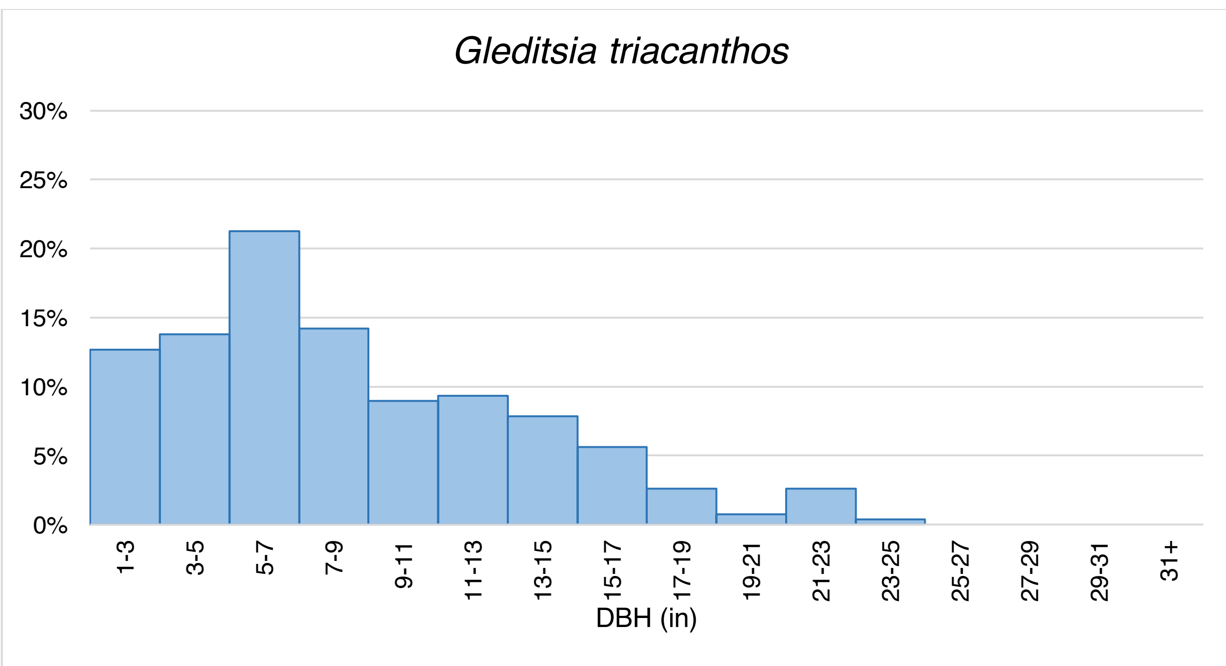

Figure 6: Distribution of DBH sizes within *Gleditsia triacanthos* (honeylocust) population.

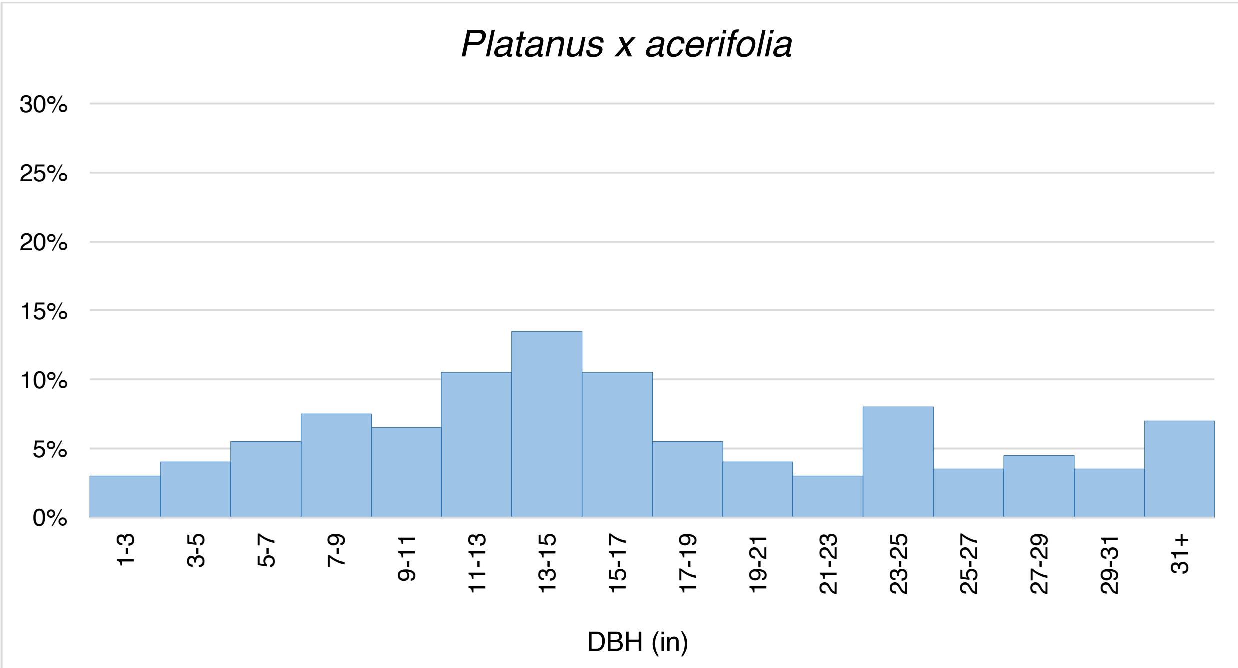

Figure 7: Distribution of DBH sizes within *Platanus x acerifolia* (London planetrees) population.

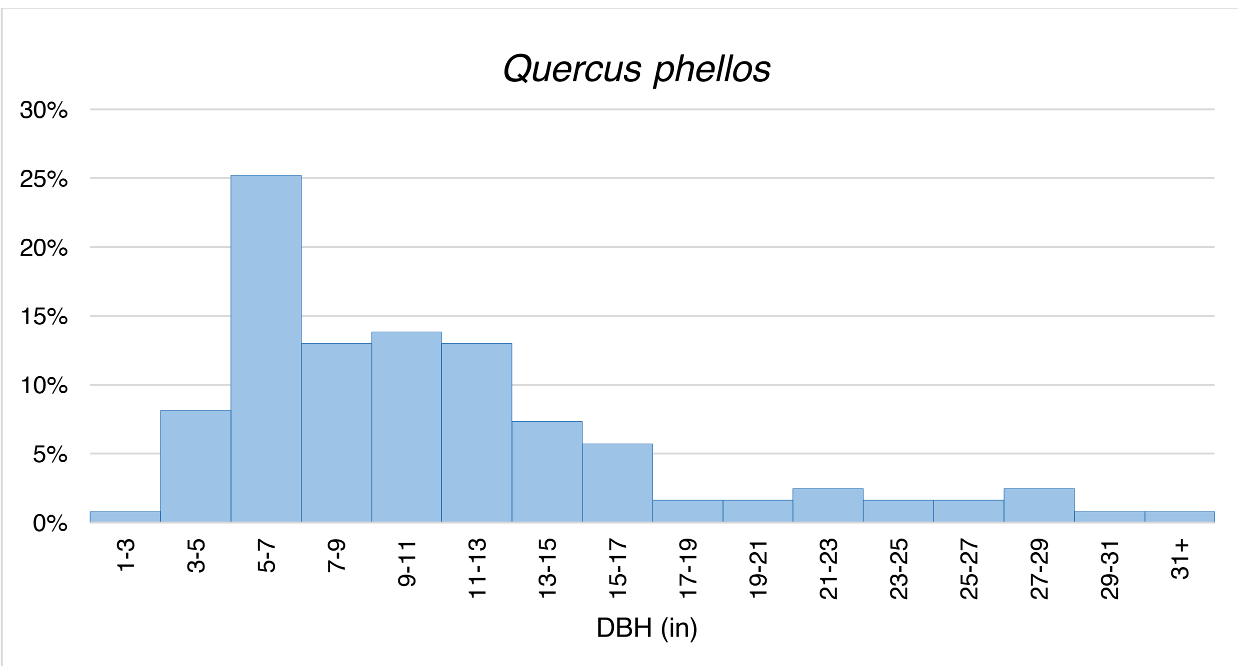

Figure 8: Distribution of DBH sizes within *Quercus phellos* (willow oak) population.

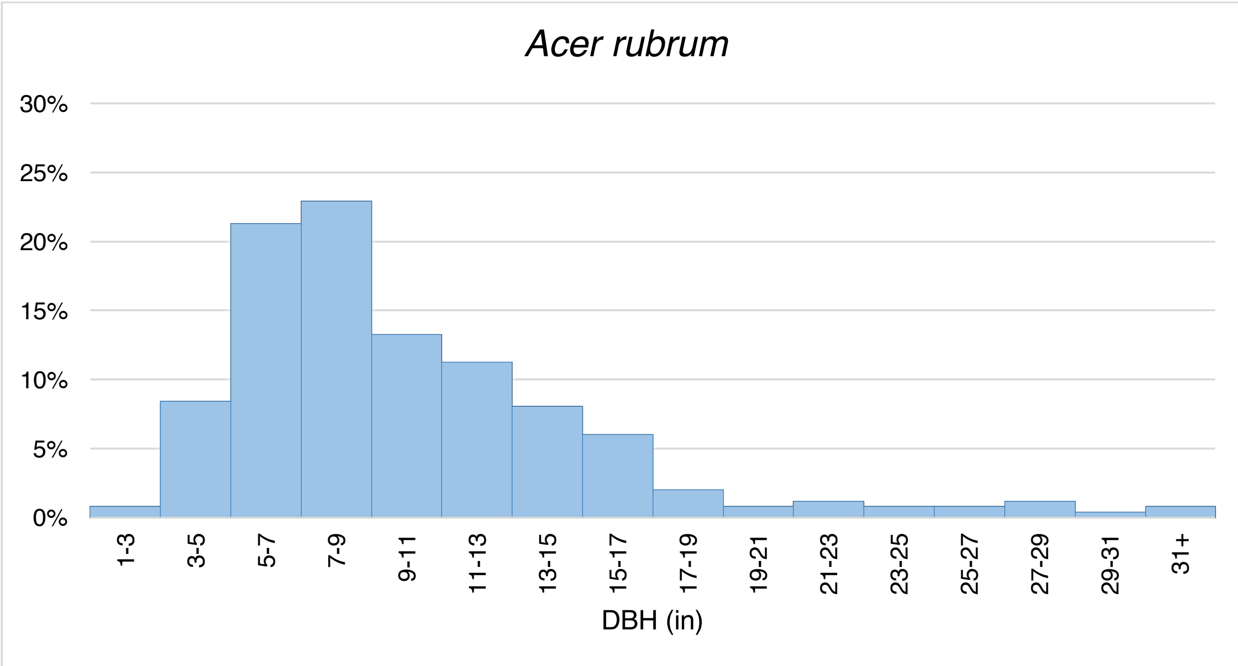

Figure 9: Distribution of DBH sizes within *Acer rubrum* (red maple) population.

Leaf Area and Importance Value

Most of the environmental benefits of trees come from their leaf surface area, which is mostly dependent on the size and species of a tree (Nowak 2007). Leaf area increases dramatically as DBH increases (Figure 10). The importance value (IV) is calculated by adding the relative abundance to the relative leaf area of a given species. *Platanus x acerifolia* (London planetree) outpaces all other species at Penn in importance value because in addition to being the third most abundant species on campus, it is mostly composed of mature trees with high leaf surface area (Figure 11). London planetrees account for the highest proportional amount of leaf area on campus compared to any species: 1,339,623 square feet of leaf area or 18.3% of the total campus leaf area. For comparison, all *Gleditsia x triacanthos*, though more numerous than *Platanus x acerifolia*, count for a total of 230,998 square feet of leaf area.

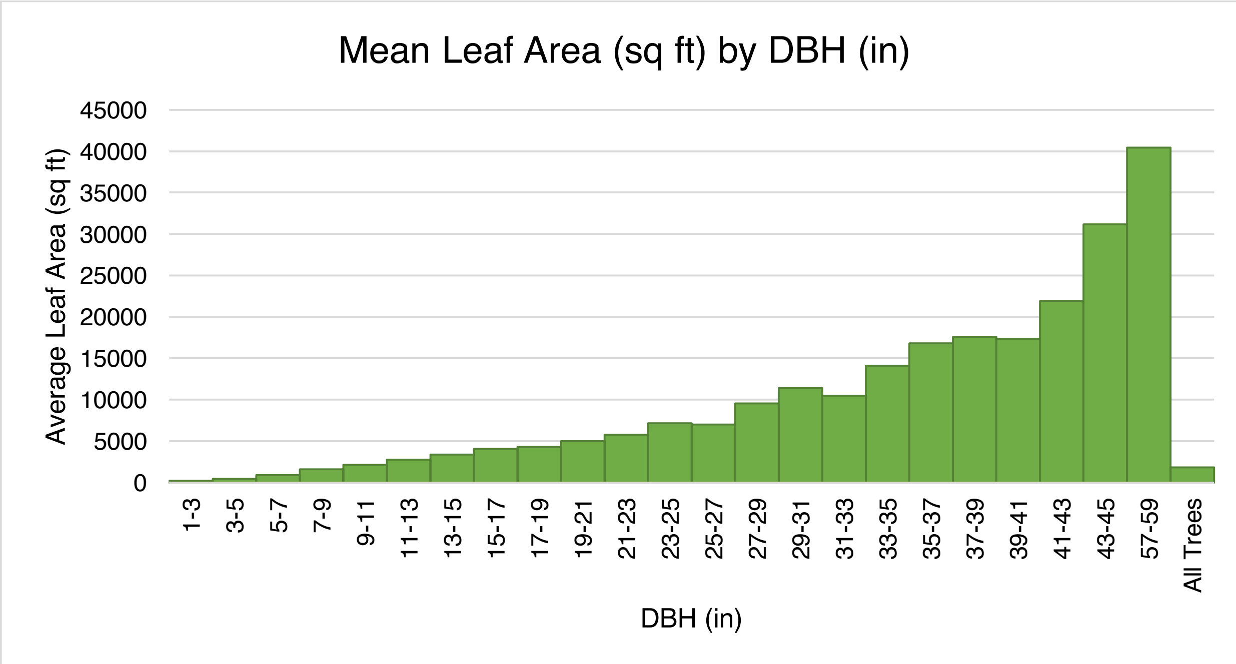

Figure 10: Mean leaf area of trees increases with DBH.

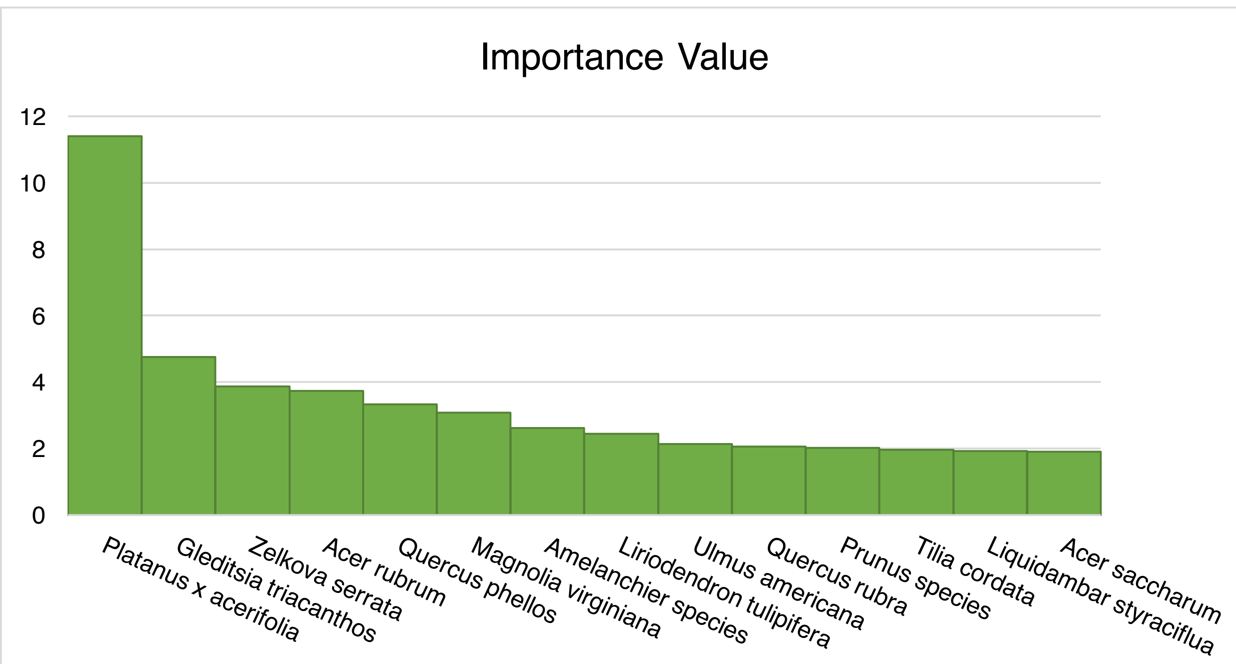

Figure 11: Tree species in descending order of importance value. This measure ranks species based on their relative importance within an inventory because of their abundance and total leaf surface area.

Air quality

i-Tree Eco calculates the amounts and values of pollutant removal by trees using a model based on local hourly pollution and weather. The model simulates how pollutants interact with leaf surfaces via deposition and gas exchange. The monetary value estimates due to improvements in air quality are derived using an adaptation of the United States Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program (USA EPA BenMAP) (iTree Tools, 2015). In total, 3,069 lbs of air pollution are removed each year by trees at Penn, with a value from improved health outcomes of $82,509. This is made up of removed ozone (O_3), sulfur dioxide (SO_2), carbon monoxide (CO), nitrous oxide (NO_2), and particulate matter 10-2.5 microns and less than 2.5 microns (PM_{10} and $PM_{2.5}$, respectively). The most significant value came from the removal of $PM_{2.5}$, which accounted for a $38,156 benefit.

Avoided stormwater runoff

An estimated 166,913 cubic feet per year in stormwater runoff is prevented by the Penn campus trees. This avoided runoff has saved approximately $11,112 in expenses, using an estimated value of $\$0.067/ft^3$ of avoided runoff, a conservative national average for stormwater-related costs and damages (i-Tree Tools, 2015). Bigger trees with larger leaf areas had a larger impact per tree than smaller trees with smaller leaf areas.

Building energy savings

A total value of $51,871 is saved in heating and cooling costs from campus trees each year. 1,201 trees, 29.3%, of the 4,086 trees included in the study did not contribute to savings because they were either not large enough or not close enough to buildings. The species that contributed the most to energy savings were *Gleditsia triacanthos* (honeylocust), *Platanus x acerifolia* (London planetree), and *Acer rubrum* (red maple) (see Table 2). However, the species with the highest average savings per tree were species of which there were only a few very large specimens in the Core Campus. Notably, the three *Cedrus atlantica* (blue atlas cedar) on campus have the highest average value of any species at $243 in energy savings per tree per year.

Trees can effect building heating and cooling costs by shading them in the summer, sheltering them from winter winds, and lowering ambient temperature through evaporative cooling. While on the whole, trees contributed positively to building energy savings, select trees had a negative effect on the overall cost savings. Trees that shade buildings in the summer and reduce air conditioning costs may continue to shade buildings in the winter as they block heating from solar radiation. It is also important to note that these energy savings are annual benefits. Maintaining healthy and growing trees results in increased benefits each year until they are removed.

Table 2: Species with the highest total energy savings.

	Tree Count	Sum of Heating kwh value ($)	Sum of Cooling kwh value($)	Sum of Total Value($)	Average of Total Value($)
Gleditsia triacanthos	259	1,579	2,381	6,018	27
Platanus x acerifolia	187	1,364	1,936	5,357	41
Acer rubrum	123	878	1,814	3,747	34
Zelkova serrata	126	795	874	3,184	31
Quercus phellos	123	664	1,225	2,444	24
Ginkgo biloba	68	529	791	2,223	36
Liquidambar styraciflua	72	346	704	1,520	30
Quercus rubra	52	361	700	1,455	30
Ulmus (genus)	51	387	554	1,399	35
Liriodendron tulipifera	76	327	566	1,258	22

Carbon

Carbon storage is the amount of carbon currently being held in trees. As trees grow and increase their biomass, the amount of carbon they store increases. Carbon sequestration is the yearly rate at which trees remove carbon from the atmosphere. The Core Campus trees store a total of 1,576,717 lbs of carbon and sequester 75,516 lbs each year. Looking at both numbers is important because carbon sequestration tells you how much trees are currently affecting how much carbon is in the atmosphere, while carbon storage is an indication of how much would be returned to the atmosphere if the trees died and decomposed. Mapping the carbon storage density visualizes where carbon is stored on campus (Figure 12). Because of their large and historic trees, the Bio Pond, Locust Walk, and Hamilton Walk all feature some of the highest carbon storage density areas on campus.

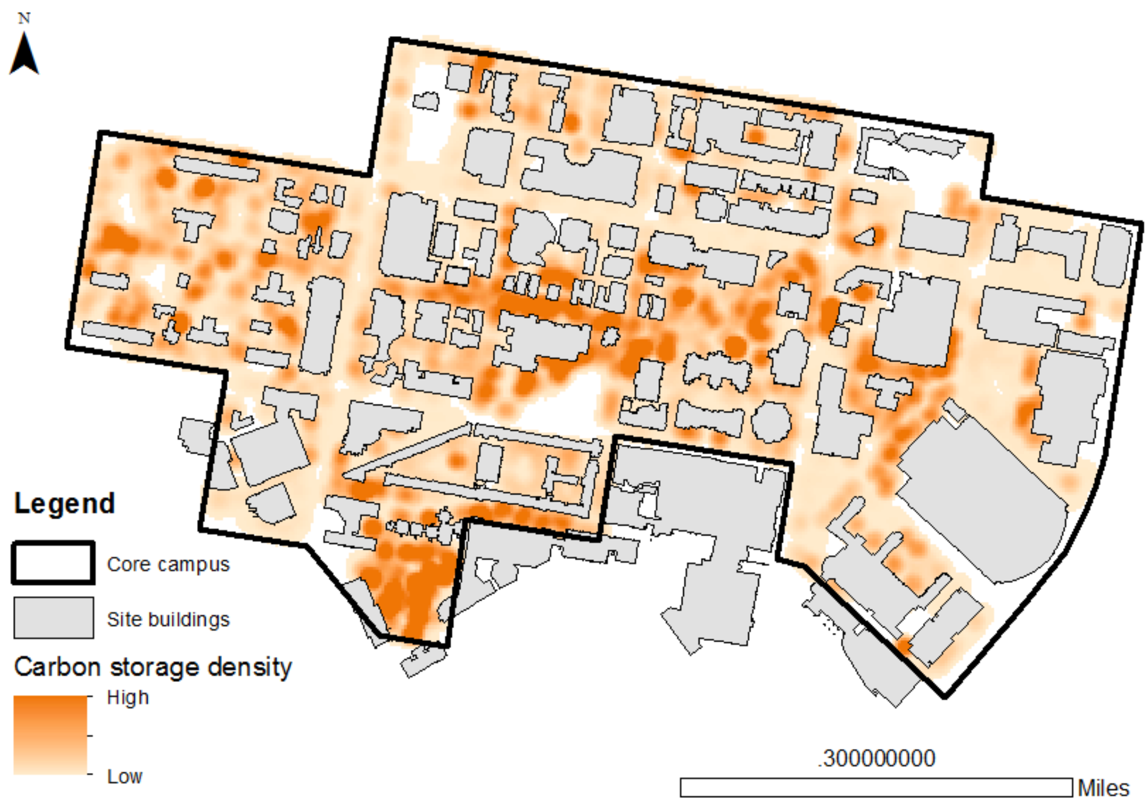

Figure 12: Campus carbon storage density. Created with ArcMap 10.3 kernel density tool.

Street Trees

Figure 13: Street trees within the Core Campus of the University of Pennsylvania.

In this study, street trees were designated as trees directly adjacent to streets and planted in tree pits (Figure 13). Out of the 4,086 trees measured, 426 were street trees. Street trees offer both unique management challenges and unique benefits to their location. Though sometimes perceived as a "public nuisance" from falling leaves and branches, their lifetime environmental benefits outweigh maintenance costs they cause. Street trees directly shade sidewalks which increases the durability of pavement, intercept stormwater that would otherwise flood sewers in storm events, and cool heat trapping streetscapes (McPherson, 2000; Roman et al., 2014).

Street trees have to be especially hardy to survive the harsh conditions of living with high exposure to pollutants, pedestrian traffic, and confined soil pits. Certain species, like honey locusts (*Gleditsia triacanthos*) and Japanese zelkovas (*Zelkova serrata*), are well known for their suitability as street trees and thus make up a significant proportion of the street trees at Penn (Figure 14). However, new species or new tactics for growing street trees could remove some of the risk associated with relying on a few species to make up most of the street tree population. The distinctive role of street trees in comparison to other campus trees is important to stress because the i-Tree Eco benefits model does not completely capture their outweighed positive environmental influence.

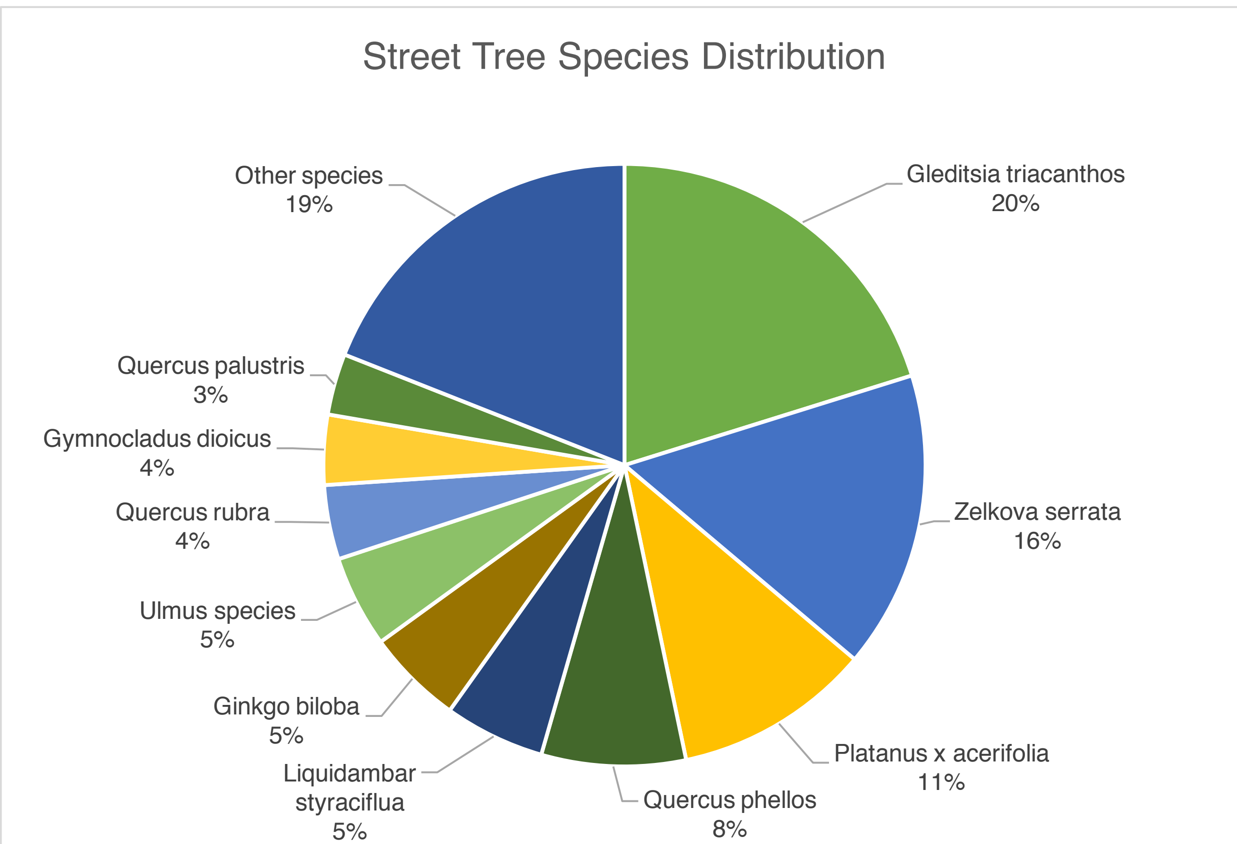

Figure 14: Species of street trees within the University of Pennsylvania Core Campus.

Discussion

i-Tree Eco assessments provide huge amounts of information to institutions on their tree inventories. Because trees at Penn are already well documented, the most useful data from this project for the University will be the data on leaf area, energy savings, contribution to air quality, stormwater management, and carbon storage and sequestration. However, it is important to realize that each of these environmental benefits is a part of the greater picture of how trees benefit their surrounding communities. Like any model, the i-Tree Eco model has limitations and can not capture all of the benefits of trees, nor does it take into account all the costs of trees in communities. Highlighting one factor as the single most important takeaway would be an incorrect interpretation of these results. Each section stands together to define the ecological role of trees on Penn's campus. Trees have the potential to contribute great returns on investment to an institution like Penn, provided they are managed to maximize their full range of services. A major goal of this project is not only to inform decision makers at Penn of the benefits and value of urban trees, but to help guide future urban tree management practices.

The results clearly show the importance of London planetrees (*Platanus x acerifolia*) on campus. Their abundance, relatively large size, and high leaf area are what make their survival essential to the Penn urban forest. Of the 276 large trees within the Core Campus over 20 inches in DBH, 65 are London planetrees (23.5%). To decrease the reliance on London planetrees as such a major part of the mature canopy, other species capable of obtaining similar size need to be preserved to join and replace them. As evidenced in Figure 7, there are not enough proportionately smaller London planetrees on campus to replace the mature trees when they eventually die or need to be removed. Waiting until current trees die to replace them means waiting decades to recoup their lost benefits. Without maintaining adequate numbers of middle

Figure 15: London planetrees in front of the Palestra in 1956 (University Archives, 1956)

sized trees and planting new trees, the benefits from London planetrees will decrease over time, and thus a significant portion of overall Core Campus tree benefits.

Six historic London plane trees near the entrance to the Palestra were preserved during the new construction of adjacent Shoemaker Green, completed in the fall of 2012. Shoemaker Green is hailed as one of Penn's most impressive green infrastructure projects (Lundgren, 2015; Hahn, 2012). Most of the publicity and praise have been for its underground stormwater retention basin, vegetative rain garden, and native plant landscape, ignoring the preservation of the six existing London planetrees. The combined structural value of these trees is $31,748. These six trees together store 14,291 lbs of carbon and continue to sequester 470 lbs of carbon each year. For comparison, the 1,316 small trees between 1-4 inches DBH in this study store a

Figure 16: The new Shoemaker Green, completed in 2012, in front of the Palestra with center city Philadelphia in the background. Six historic London planes, the same trees as the ones in Figure 15, are several times larger than the new trees planted in the Shoemaker Green project (Andropogan Associates, 2012).

combined total of only 16,567 lbs of carbon. The fact that six large trees can almost encompass the benefits of 1,316 small trees supports that growing trees to large sizes should be a management priority.

A 1956 photo of the front of the Palestra shows these six London planetrees as well established mid-sized trees (Figure 15). They are believed to have been planted at the end of World War II, about eighty years ago (Lundgren, 2015). In 2015, they stand at an average of 80 feet tall, provide shade to a total 12,670 ft^2 of ground area (Figure 16), preserve the history of the Palestra, and add maturity to the new Shoemaker Green. Had these six trees not been saved in the construction of Shoemaker Green, their benefits would have been irreplaceable within decades. Penn is continuing to reap greater and greater rewards from these saved trees each year as they grow and their annual environmental benefits increase.

Platanus x acerifolia (London planetree) is not the only large mature tree species with individual trees that convey substantial benefits. The Penn Treaty Elm on College Green in front of College Hall is the most well known, historic, and valued tree on campus. It was propagated from plant material originating from the American elm under which William Penn signed a peace treaty with the Lenape tribe in 1683. In addition to the elm's storied history, it has some of the most significant environmental values of a single tree on campus. Today, it is the largest and oldest elm on campus. Looking at all the *Ulmus Americana* (American elm) in the Core Campus by DBH compared to their carbon storage and leaf surface area (Figure 17), the Penn Treaty Elm's size cause it to surpass all others in terms of ecological benefits. Figure 17 can also be used to project what the benefits of small elms recently planted will be as they grow, and shows the increasing rate at which 20-40 inch DBH elms are providing benefits.

Though the Penn Treaty Elm has obvious intrinsic value to the University that make it a maintenance priority, it provides an example of the benefits of allowing trees to achieve mature stature through consistent and continued care and effort. Though planting trees is the necessary first step, the extraordinary bnefits of large shadetrees will never be gained without a long term vision for their growth. Trees continue to convey more and more benefits as they age – all of which halt or become negative when trees are removed. Preserving trees has immediate benefits and prevents immediate losses.

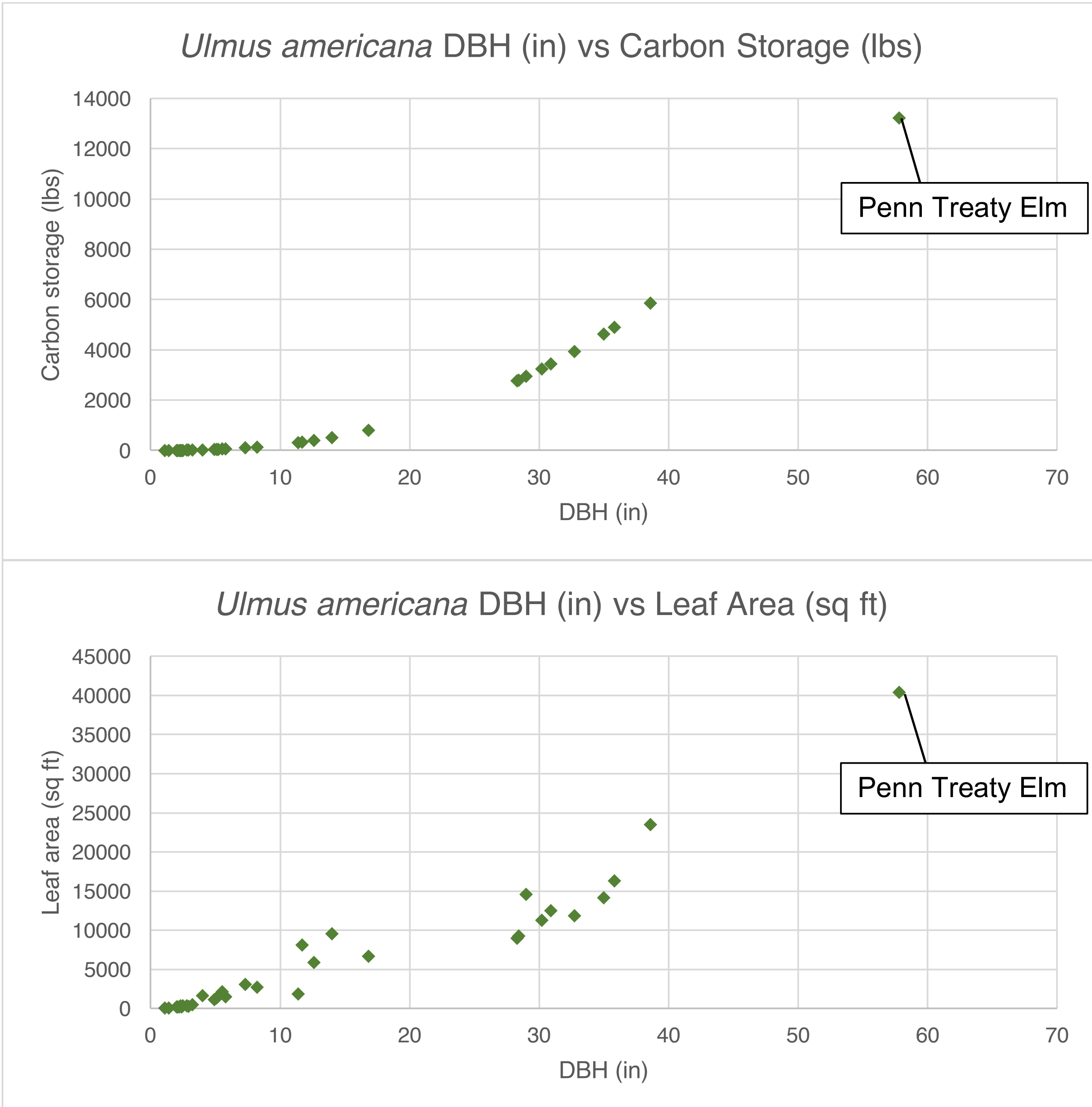

Figure 17: *Ulmus americana* (American elm) trees at Penn with larger diameters have greater leaf areas and store more carbon per tree than elm trees with small diameters. The Penn Treaty Elm surpasses all other elms in size, carbon storage, and leaf area.

Conclusions

Trees are not solely an aesthetic asset to campus, but instead as a substantial portion of Penn's sustainability initiatives. Trees play a role in the cycle of carbon on campus through storing carbon, sequestering carbon, and reducing building energy use. In the Physical Environment Recommendations section of the Penn Climate Action Plan 2.0, tree conservation priorities are clearly stated, in addition to carbon emission and energy use reduction goals. Building-related utility usage is the largest source of Penn's campus carbon emissions (~85%) (University of Pennsylvania 2014). The effect of trees on reducing building electricity and steam use should be part of future plans to reduce building carbon emissions on campus. Trees can be planted strategically to maximize their impact on building energy use and managed to be healthier and longer lived to maximize the carbon they sequester.

Tree survival at Penn is highly affected by urban environmental stresses on trees and tree removals due to new construction projects. The benefits lost to past removals are unknown, but this study will help capture the true costs of losing specific trees in the future. New trees are planted every year at Penn, but whether the benefits of new plantings outweigh the losses from removals each year is also unknown. With this study, Penn's plant management practitioners have data on all of the existing plantings at Penn and will be able to track the progress of these trees into the future. Repeating this study in the future would allow for a deeper understanding of Penn's urban forest dynamics.

As the Penn campus changes and expands over the coming years, the urban forest will certainly change with it. Additions of land are increasing the size of the urban forest Penn will need to manage. The construction of new buildings is both putting existing trees that conflict with new projects at risk and providing opportunities to plan new sustainable landscapes.

Campus trees are an environmental and ecological asset that should be incorporated into Penn decision making processes and the sustainability goals stated in the Penn Climate Action Plan 2.0.

This study sets a precedent for future studies of the Penn urban forest, including Penn's peripheral campuses: the Penn New Bolton Center, the Morris Arboretum of the University of Pennsylvania, Penn Alexander Elementary School, and the Penn Medicine hospital system. Making the data collected and methods used this summer accessible to future projects is crucial for the expansion of Penn's tree programs. Penn has the opportunity to be a leader in urban university tree management.

i-Tree Eco puts a powerful tool into the hands of institutions around the world to understand the value of one of their own natural resources: trees. Maximizing strategic tree placement and management can maximize received benefits. The University of Pennsylvania has already taken major strides towards creating a more sustainable campus and maintaining its urban forest. However, in the dense setting of University City where space is at a premium, new construction and development on Penn's campus are often at odds with the desire and need to expand Penn's tree programs. Trees at Penn are an ecological asset in the context of a rapidly changing neighborhood and should be more fully valued. This project demonstrates that investing in the maintenance of current trees and planting new trees will continue to generate real world benefits in the future to Penn and its urban ecosystem.

Appendix

i-Tree Eco Results Summary

Campus Forest Structure

- Top 5 most common species: *Gleditsia triacanthos* (honeylocust), *Magnolia virginiana* (sweetbay magnolia), *Platanus x acerifolia* (London planetree), *Amelanchier sp.*(serviceberry), and *Zelkova serrata* (Japanese zelkova)
- Trees measured: 4086
- Area assessed: 160 acres
- Percentage of small/young trees <6 inches in diameter: 52.03%
- Average leaf area of all trees: 1,789 ft^2
- Median leaf area of all trees: 699 ft^2
- Average leaf area of trees ≥31" DBH: 16,408 ft^2
- Highest leaf area per species: *Platanus x acerifolia*, accounting for 18.3% of campus leaf area

Campus Forest Benefits

- Total carbon storage: 1,576,717 lbs
- Average carbon storage of all trees: 385 lbs/tree
- Average carbon storage of trees ≥31" DBH: 6,074 lbs/tree
- Annual gross carbon sequestration: 75,516 lb/year,
- Annual $PM_{2.5}$ removal: 104 lbs/year ($38,156/year value)
- Annual total building heating/cooling cost reduction: $51,871
- Median structural value of a Penn tree: $609
- Total structural value of Penn trees: $4,979,709

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