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A Comparative Evaluation and Application of Established Urban Carbon Sequestration Tools

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a thesis submitted to the Faculty of Emory College of Arts and Sciences
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Abstract

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With urban area increasing and urban environmental quality concerns growing, land-owning institutions within densely developed space experience pressures against allocating natural land or advocating for green space. Given the significance of carbon emissions in global climate change, urban managers recognize the potential for managed areas to offset these emissions and impact urban environmental management and policy. This work seeks to assist the study area, Emory University, in selecting and implementing land management solutions that contribute positively to the resilience (ecological health) – and human well-being – of the urban system through a comparison of evaluation methods for estimating carbon sequestration and other ecosystem services.

This study compares well-established ecosystem service estimation tools, I-Tree Tools, to evaluate the suitability of each tool to Emory. I then recommend alternative exterior development priorities and strategies for supporting carbon sequestration, long-term-storage, and non-carbon ecosystem services on Emory's campus. This study finds that I-Tree Canopy is most suited to a mixed land area such as Emory, as well as being the most user friendly relative to the reliability of its output. If variable output and data are needed, I-Tree Eco bridges the physical gap and estimates based on field data.

Ecosystem services describes the natural benefits that humankind can obtain from an ecosystem. In this case, forested land alone stores approximately 50,510 tons of carbon (valued at $1.826 million) and sequesters 2,318 tons annually, nearly offsetting the annual emissions from Emory's fleet vehicles, totaling 2,472 tons. Emory's trees and forests have the potential to remove 10.44 tons of ozone (O_3), 2.52 tons of PM 10 air pollution, and 1,276 pounds of PM 2.5 air pollution annually. Prioritizing large biomass tree species selection and continuing to expand overall vegetative and tree cover will benefit all facets of Emory's University system and healthcare network, including working toward a larger emissions offset project.

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Contents

Introduction

The widespread environmental changes associated with increased greenhouse gas emissions have signaled the need for urban planners to quantify the ability of everyday urban green spaces to combat emission impacts, air pollution, and mitigate other concentrated urban ills (Vandermeulen 2011, McPherson et al. 2005). Starting in 2007, a cohort of 100 cities, including New York, Atlanta, Los Angeles, and Chicago worked with researchers and urban policymakers to manage their cities and better plan for unpredictable human and climate related impacts (City Resilience Framework 2015). One result of this collaboration was the City Resilience Framework, an ecological and economic framework that organizes specific driving factors for city resilience into basic levels and subdivisions. The framework allows urban planners to use this collective knowledge to better assess the complexity and socio-ecological resilience of their cities by pinpointing areas of weakness and suggesting potential solutions. Actions like allocating natural land (a strong driver of urban ecological health) and maintaining adequate water, energy, and transportation infrastructure are paramount in the sudden event of a storm, or a long-term environmental disaster like drought. Within these cities, landholding institutions can further develop this idea of building resilience as a way to offset concurrent emissions from development and sustainably expand through long-term, multi-phase biomass expansion, or urban ‘greening’.

Processes that naturally help regulate air pollution, buffer heat, and manage annual emissions add a quantifiable benefit to urban greening. Given the significance of carbon emissions in global climate change, urban managers have begun to recognize the potential for managed areas to offset impacts associated with these emissions. Carbon sequestration is an ecosystem service that traps and stores carbon as biomass (leaves, branches, and soil) and can help offset carbon dioxide emissions from motor vehicles, industry, homes, and offices. Urban-residential forests within the U.S. may sequester up to 56.1 million tons of carbon annually, contributing to total carbon uptake at a nationally significant level (Nowak and Crane 2013). While often conflated as two parts of a larger carbon uptake process, the process of active sequestration and the accumulation of stored carbon are distinct benefits to be managed for within urban forests. In the primary software used in this work, carbon sequestration refers to a rate that results in an amount of carbon that will be added to the total stored carbon within the trees, while carbon storage is a static amount of carbon within a tree's biomass at a specific point in time (McPherson 1993, McPherson 1998). Both these estimates demonstrate carbon within the biomass of trees (above as branches and below ground as roots) but specifically excludes estimates of carbon in soil and other vegetation. Sequestration and the subsequent storage of this carbon are two of a myriad of ecosystem services and intrinsic natural benefits for a whole ecosystem. In order to demonstrate the benefits of an urban ecosystem to someone unfamiliar with the inherent, biological value of forests, tools that use the ecosystem services framework display data as functional, easily understood monetary values.

Ecologists have recently made a tactical development by assigning monetary values to services provided by ecosystems for "free" in a process called valuation. Land-managing institutions such as healthcare conglomerates, universities, and office campuses have the unique opportunity of managing green space in areas that are increasingly losing available land to commercial projects with little tangible ecological benefit. Economic valuation gives managers a new tool to represent the social, economic, and ecological benefits of urban trees. Further monitoring can assist in developing institutional management practices, which could then incorporate assessments of and. adjustments to management practices based on system changes (Vandermeulen 2011, Tyrvainen 1998). Forested areas within the United States near metro areas have been shown to buffer some of the impacts of concentrated human development, but urban greening needs to become more extensive for the return on investment to be effective and significant (Jim and Chen 2009). As outlined by Jim and Chen, ascribing an easily understood value (monetary or otherwise) to the positive and productive aspects of natural systems can "permit a direct comparison between alternative land use options," facilitating an increase in those beneficial natural areas as opposed to a development with little environmental benefit.

Ecosystem services, the concept underlying ecological valuation, describes the array of natural benefits that humankind obtain from a natural system. This framework of looking at organism processes as benefits to humans is centered on management but is rarely applied by decision makers when evaluating a potential project that uses natural land for other development. Applications of the ecosystem services framework quantify the human benefit of specific organisms and their actions, and represents these services as a monetary value needed for an organization to perform said service in the absence of those organisms (Bastian 2012, Escobedo 2011). For the purpose of this research on urban trees at Emory University, common ecosystem services include carbon sequestration and storage, air pollution removal, energy-use reductions in buildings, avoided stormwater runoff, and oxygen production.

Emory University, in Atlanta, GA, is an institution whose commitment to urban sustainability has historically been indicated through the establishment of a university Climate Action Plan and long term sustainability vision ('A Plan for Climate Action' 2011, Emory Sustainability Vision 2016). Emory's relatively extensive natural land may help to buffer heavy traffic air pollution effects near medical plazas and the Centers for Disease Control. Emory's campus was selected as a study area due to its proximity to metropolitan Atlanta, a city working to increase its responsiveness to environmental challenges, and return on its proven commitments to monitoring emissions and environmental quality.

Recent projects including the Emory Healthcare expansions, the renovation and extension of university admissions centers, and numerous building replacements could easily be described as infilling; increasing the density of existing areas by filling in "gaps" and using building updates rather than expanding held land. The benefits of reforesting campus land or maintaining natural education areas are not often considered within a general evaluation of a potential project, though impacts on total forest canopy are considered through Emory's No Net Loss policy, where the University replaces cut trees. Ecosystem monitoring is more common for those with commercial forest stocks, but urban institutions could benefit from gathering ecological information on their campuses to know what daily processes of the forest affect costs.

Urban ecologists and exterior development employees use valuation to bridge this natural-commercial gap and effectively represent valuable natural processes to non-ecologists. Case studies in Finland, China, and the U.S. have established that, with the correct management of plant selection and nutrient monitoring, urban forests can significantly contribute to carbon storage and net annual carbon sequestration (Kuittinen 2016, Liu and Li 2012, Tyrvainen 2001, Zhao 2010, Zheng 2013). In the U.S, $4.4 billion was estimated to have been saved from avoided and decreased building energy use and other services (Nowak et al 2013, Nowak and Crane 2002). In fact, researchers found that urban landscape-integrated single and street trees, regardless of lawn/other vegetation contributions, could sequester between 20 and 40 million tons of carbon each year nationwide (Jenkins and Riemann, 2003).

Moreover, ecological valuation could easily assist beyond carbon sequestration in urban tree expansion in areas where carbon emissions are not a priority, but rather other natural benefits are more impactful to the community; for example, urban trees can be responsible for pollution mitigation, potential energy savings, and stormwater management benefits (Brack 2002, Lovasi et al. 2013, Muller 2007, Paoletti et al. 2010). Trees help to stabilize creek banks, increase groundwater absorption, decrease energy usage/spending by shading buildings in hot climates, buffer urban noise, and decrease particulate air pollution of two size categories (PM 2.5 and PM 10 micrometers) (Bolund and Hunhammar 1999). The social and wellness benefits of trees are beyond the scope this work, but are significant in highly developed at-risk urban areas. Interestingly, the perceived benefit of urban greenspace development extends beyond the natural ecosystem and into the social sphere; researchers have observed various associations between physical green space and decreased crime, increased feelings of wellbeing, and community cohesion (Weinstein et al 2015, Foley et al 2005).

This work seeks to assist Emory University in selecting and implementing land management solutions that contribute positively to the ecological health – and human well-being – of the urban system through a study. This work compares software within a set of well-established ecosystem service estimation tools, to evaluate the ease of use and relative suitability of each tool for Emory’s needs, and allows this analysis to serve as a recommendation for alternative development priorities and strategies for ecological support on Emory’s campus. These recommendations that stem from Emory’s unique institutional priorities and its current strengths act to bolster the natural ability of university lands to preform carbon sequestration and other beneficial ecosystem services.

Through the evaluation process, this work strives to increase the overall knowledge of and subsequent adoption of these tools by communicating the experience of completing an inventory/estimation for a specific campus area. A realistic depiction of this experience can provide management employees a better time and labor estimate before beginning a process, in turn making the process more accessible and achievable. Continued monitoring and management of urban tree benefits can therein become integrated into institutional priorities as a quantified way to economically support urban greening initiatives. More specifically, this thesis will evaluate the potential economic and ecological benefits of urban greening by focusing on the following research questions:

- From an array of accessible tools, what tool, or combination of carbon estimation tools, is most appropriate for establishing a baseline carbon assessment of Emory University?
- What actions could the University take to further support its urban ecosystem functionality?
- What issues in future research on urban ecosystems and management ought to be prioritized for the greatest positive impact on institutional ecological practices?

Methods

Study Area

Emory University's campus is within the Atlanta, GA metropolitan area, in Druid Hills, GA. Atlanta is in the Piedmont physiographic province of the United States characterized by red clay soils, fast spreading vegetation, Oak-Hickory-Pine forests and moderate year-round rainfall (NWS Scorecard 2016). Emory manages 735 acres of land, 42% of which is designated preserved by the University, including Lullwater Preserve, an extensive urban forest near the Emory Healthcare medical facilities, and Baker Woodlands, a small natural wooded area near the heart of campus.

The Emory University system includes the Emory Healthcare network with many facilities directly adjacent to the main Druid Hills, GA campus. The presence of these facilities greatly affects land use priorities but also incentivizes efforts to reduce negative urban effects of pollution near facilities. Pollution removal, oxygen production, aesthetic, and recreational benefits may be of greater importance to the Emory Healthcare community and subsequently the University at large.

Tool Selection and Comparison

I chose to comparatively evaluate two tools from a set of ecosystem services assessment tools (I-Tree Tools) with criteria derived from consumer product standards [Table 1]. Table 2 outlines other specific tools that were excluded from this comparative evaluation as well as a summary of their suitability for campus and data output. From a multitude of available tools, I narrowed my search to tools created by environmental organizations or universities, and then further refined with my criteria. I chose these criteria to better describe the function, ease of implementation, and time commitment of these tools to those someone who working to produce an estimate for an organization.

I selected a subset of carbon assessment tools, I-Tree Eco and Canopy, created by the US Forest Service and researcher David Nowak (I-Tree Tools 2017). This set was not only the most appropriate in terms of software purpose and function, but also the most recommended in my co-citation analysis and in my tool search for in-depth urban carbon estimates. Out of this set, I-Tree Canopy was selected due to its availability and convenience as a web-based application, and I-Tree Eco was selected due to its available complexity and robust methodology-based estimation. For a comprehensive description of the Urban Forest Effects (UFORE) methodology that this software uses to generate its carbon, pollution abatement, and other ecosystem benefits, including monetary value determinations, refer to Appendix 1.1 through 1.4. Both models rely on literature estimates and the US EPA's BenMAP for valuing pollution impacts (avoided adverse health outcomes). Following this preliminary evaluation, I-Tree Eco is more apt at inventory based on field survey work or existing, supplemented inventories, making it an appropriate next-step in analysis for an institution with a previous tree inventory, like Emory.

Survey Work

As an efficient first step in completing an inventory of campus trees for a tool in the selected set, I-Tree Eco v.6, I worked from a previous tree inventory of campus completed by a third-party tree management company, ArborGuard. This initial survey included main campus as defined by main bordering streets [Figure 1]. Figure 2 is an image of the survey area for Canopy's measurement of forested areas, a method that uses satellite imagery and cover estimates. I collected data on two additional variables for the trees surveyed: distance from/direction to a building (0-60m, 0-360), and crown light exposure, or how many sides of the live top of the tree are generally exposed to light (1-5). These building variables allow Eco to generate estimates for energy savings by estimating building shade at various times in the year, while crown light data helps Eco refine carbon sequestration estimates for full sun and shaded trees [Table 3].

Carbon Estimates and Recommendations

Following selection, I-Tree Canopy/Eco were utilized to estimate three different inventories for Emory University's Main Campus: 1) campus as defined by major perimeter roads, 2) exclusively Emory's forested areas, and 3) a full campus area including a combined inventory that adds Emory's forested property with I-Tree Eco's estimate of main campus trees benefits.

Canopy uses aerial photographs to estimate cover percentages of tree canopy, and other selected surface categories. After determining a sample area polygon (an outline of the area), a user can add data points by generating an aerial image of a random location within this study area and categorizing it as a type of surface cover (Forested Tree, Vegetation, Roof, etc.). Increasing the number of sampled data points decreases the standard error, and makes the resulting cover estimates and benefits more representative. Eco is a desktop application that uses manual survey data (individual tree) or sample plots of forested areas to generate descriptive statistics and reports for administrative, management, or maintenance use. The U.S. EPA's BenMAP was used to estimate the incidence of adverse health effects and associated monetary values resulting from changes in NO_2, O_3, PM2.5 and SO_2 concentrations within Eco.

With these estimates and a review of University publications regarding sustainable goals and development, I described applications for these tools and this type of inventory work, and recommended campus ecosystem management/monitoring actions to increase the ecological and human benefit of Emory's extensive tree canopy.

Co-citation Analysis - VosViewer Software

To 1) create a visual representation of the ongoing research into the field of urban forestry/emissions management and 2) situate my selected tools within the larger literature, I compiled citation data from a database literature search and used VosViewer bibliographic visualization software to create a map of these references that displayed related work in distinct authorship groups, or clusters (van Eck 2010). I then evaluated the position of this thesis within related publications by generating a co-citation map, where articles are linked by their included references, and examining the composition and priorities of urban forestry and emissions management. 404 references were downloaded from the ISI Web of Science database with an advanced search with the terms "urban+carbon+sequestration", restricting results to articles and reviews and generated a co-citation map clustered based on these references. VosViewer uses the citation data of individual references (papers or reviews) to determine which authors draw closest upon each other's work. I then used the metadata (number of authors in each group, common journals, research subject areas, etc.) from these references to answer the following inquiries about the current field of urban emissions management:

- Composition: What are the distinct groups of work, and how distinct are they from each other?
- Division: Is there a divide between quantitative and qualitative research, applied and basic data oriented?
- Place: How does my work align with the scientific and social priorities of recent research?

Results

Initial ArborGuard Survey

As an initial step toward sustainable development and more comprehensive tree maintenance on campus, Emory Exterior Services authorized ArborGuard Tree Services to measure and inventory trees in a portion of the main campus property. 887 trees along with six sample plots of approx. 10% of the total area from several “densely wooded areas” on campus were included in the report but no methodology was included with the resulting dataset or generated report as to the location, distribution, or composition of these plots (ArborGuard Tree Specialists 2015). It is unclear as to whether these sample plots were from larger wooded areas such as Lullwater Preserve or exclusively wooded areas within the defined main campus.

ArborGuard determined that those 887 individual trees, as well as the representative sample plots, store 722,239 pounds of carbon (overall, not annually), yielding a structural or replacement value of $1,664,810.00. Of management interest are the tree species with the highest levels of annual sequestration including Water Oak (*Quercus nigra*), Red Maple (*Acer rubrum*), and River Birch (*Betula nigra*). On annual terms, the included trees sequester approximately 24,708 pounds of carbon and remove approximately 1,559 pounds of combined air pollution (NO_2, O_3, PM10, SO_2). No further methodology on air pollution calculation was included in the ArborGuard report.

I-Tree Canopy

To assess both the forested and developed areas of campus with this method I conducted three separate analyses in Canopy to assess different areas (full property, main campus area as defined by ArborGuard, and only forested areas) with 400 satellite images to produce each estimate. From these 400 images, approximately 51% of the Emory area is forest cover, with an additional 9.7% of this area covered in landscaped trees [Table 4]. With over 60% of Emory's total area in tree or vegetative cover, Emory has excelled at mitigating extensive areas of its impervious surfaces such as surface parking lots or road cover. However, only 38.2% of the main campus area is covered by trees or vegetation, leaving 61.8% as roof cover or impervious surface such as pavement [Table 5], a stark difference from the composition with forest areas included from the total area.

Of specific management interest are Emory's forests, which can be monitored and managed to increase annual sequestration and long-term carbon storage. Table 6 enumerates the carbon and non-carbon benefits from forested lands at Emory; forested land stores approximately 50,510 tons of carbon and sequesters 2,318 tons annually. This storage of carbon in Emory's forests, regardless of replacement or structural value, was estimated at a value of at least $1,826,426, a substantial show of both avoided emissions and avoided cost for the University.

According to Emory's most recent greenhouse gas inventory (FY2012, completed in 2014), Emory's CO_2 emissions total around 304,754 metric tons annually, with projected increases from expanded air travel and campus transportation. As an offset to those emissions, Emory's forests sequester 2,333 tons of CO_2 annually, almost countering the emissions from Emory's fleet vehicles, totaling 2,472 tons (GHG Executive Summary 2014). It is important to note that while this sequestration represents a reduction of less than one percent of the total University's emissions, its contribution is comparable to eliminating one category of emissions of a similar size to fleet transport. To offset into the future, Emory could expand its urban canopy and vegetation in conjunction with major travel or transportation emissions increases.

The value of pollution abatement was also estimated in Canopy using tree cover estimates from Emory's campus. Emory's trees and forests potentially removed 10.44 tons of ozone (O_3), 2.52 tons of PM 10 micrometer air pollution, and 1,276 pounds of PM 2.5 micrometer air pollution, demonstrating a cost-savings of $68060.35 annually from improved health outcomes [Table 6].

The largest limitation to I-Tree Canopy and its estimates is that it only creates a simple baseline estimate; reported pollution and carbon values are calculated with only relative size and without specific information on tree species or health. Due to this limitation, these estimates may overstate or not reflect/account for the total benefit of Emory's forested areas. This is not to say that these estimates may not be used for management, analysis, or in conjunction with I-Tree Eco estimates, but that they are a less refined estimate from a simplified version of the same carbon and air pollution methodologies.

I-Tree Eco

From the initial ArborGuard survey, I gathered two more categories of data associated with the original 887 trees to increase the comprehensiveness of the results: crown light exposure (measured by the amount of crown with direct sunlight exposure at midday) and direction/proximity of any buildings to the tree (to estimate building shade energy savings).

Eco serves as a direct comparison of the way two different tools (Eco and ArborGuard's method) portrayed the carbon benefits of the same set of trees. The amount of stored carbon and the annual rate of sequestration are reported at the species, or individual level in Eco [Figure 3]. Of the 355 tons of carbon stored in landscaped trees, 51% is stored in just three species: White Oak, Water Oak, and Loblolly Pine [Figure 3]. These same species, as well as others that are extensive on campus, also comprise the largest gains in sequestration, as shown by species in Figure 4. Large biomass tree species act as long-term reservoirs for carbon that is sequestered annually on Emory's campus. Emory's main campus trees alone store carbon which has an associated value of $47,300.

In combination with I-Tree Canopy's estimates of Emory's forests, Eco shows that Emory's complete urban canopy sequesters a consequential amount of carbon relative to Emory's campus energy use. Table 7 demonstrates a full comparison of Canopy and Eco through each study area and benefit category. Of interest was the difference in Canopy's estimate of main campus carbon benefits relative to Eco and ArborGuard's estimate. This table shows a direct comparison between each method of measurement and the resulting estimate.

Eco also can demonstrate the air quality and pollution mitigation benefits of urban forests by associating a cost-saving USD value with pollution reduction and oxygen production. Eco estimates that Emory's main campus trees remove 862 pounds of total pollution, subdivided in each individual pollutant [Figure 5]. The largest category, O_3, is also the largest category of reduction in Canopy's estimates of both forested and main campus land. Overall, the most significant pollution abatement occurs in Emory's forested areas as measured by Canopy, as outlined by category in Table 6.

Eco can further be used to provide a more holistic snapshot of benefits for a relatively small amount of data input. For the same data input as ArborGuard, Eco and Canopy function as a mixed-methods approach (remote imaging, ground inventory, and multiple internal methods for each benefit) to produce a greater variety of accessible results and descriptive tables. In addition to carbon and pollution estimates, a user can generate avoided stormwater runoff values [Figure 6] and energy savings from building shade. Due to variation in soil type and typical building energy use, the generated benefit values for energy savings and stormwater runoff function as preliminary estimates to be expanded in the future. Emory's energy usage is far from what is typical within the assumptions of I-Tree Eco, but could be integrated into a specific analysis in I-Tree Design, another software tool in the suite. Further work on campus could utilize I-Tree Hydro, a software tool that uses survey data to help manage stormwater impacts, to describe the effects of and manage stormwater. Eco's largest limitation is that is requires manual survey work, limiting projects with complete inventories to smaller square area or a sample plot format.

Comparative Evaluation of Estimation Tools

Relative to I-Tree Canopy, the accessibility or user-friendliness of Eco is questionable. While both are easy to access online, first-time users of I-Tree Eco may need to extensively consult its documentation before successfully gathering and submitting data for processing. Users could become overwhelmed with the multitude of options available in the software interface and be unable to navigate efficiently. As a direct comparison, Canopy is defined by its simplicity; one outlined study area, any number of categorized satellite images as data points, and Canopy can generate an estimate of tree cover and benefits. While Canopy's software interface is similar to Eco's, it is highly simplified to reduce options and load the web-based application smoothly with a high volume of users. On the other hand, the complexity of its interface allows Eco to accept a variety of physical data that could not be ascertained via satellite image such as health of tree or species. Canopy requires no permission procedure to manually survey or access land, but that accessibility comes at the cost of limited results and potential user error due to poor display resolution.

I-Tree Eco excels in generating a variety of flexible results of differing complexities. While this is not the most important factor in deciding to use it, it is invaluable for a manger attempting to demonstrate the myriad of benefits humans receive from green space. After the two primary pieces of data are collected (DBH and Species), the desired results can be expanded to include stormwater runoff, energy savings, pest management, and other benefits. The Urban Forest Effects Model (UFORE) used in Eco can be run with a minimum set of measurements, but a higher degree of specificity in tree data (total tree height, crown measurements and condition, crown light exposure, land use, etc.) allows the tool to make a more reflective estimate of the measured trees.

Further, Eco's reports are customizable and professional, complete with ready-to-present graphics that save administrative effort when preparing to propose biomass projects. Eco also possesses a forecasting tool to predict the benefits of a planting commitment or expansion in future seasons, a useful bargaining tool for projects with seemingly intangible long-term benefits. An organization with enough time and staff to conduct an initial full tree inventory and sample plots of any other wooded areas could append new planting data onto that dataset indefinitely to use updated benefit values annually in presentations or management reports.

VosViewer Co-citation Analysis

The purpose of this co-citation analysis was to create a visualization and description of a subset of publications within urban ecology/emissions management and to situate this thesis within the associated literature. Ecosystem services valuation and highly-localized application-based research are two strong components of these authorship groups.

Through this co-citation analysis, five distinct clusters emerged that each represented a priority or approach in research within the diverse field of urban environmental management, specifically emissions management (Figure 9). Each of the five communities possessed different research aims and concerns for sub-disciplines within recently published urban ecological services literature.

The clusters were separated commonly by the foci of prominent journals within each cluster, where the smaller clusters worked within lesser-known or more specifically-focused journals. Cluster 2, represented in the map as the green grouping, consists primarily of authors who work to define the basic methods and datasets associated with translating forest-based sequestration data for urban use. The most cited article in the field and in this cluster, Nowak 2002, was published by the creators of the I-Tree Eco suite and the ground-based Urban Forest Effects Model. This co-citation analysis finds that the compared models are based upon fundamental work and are prominent within this selection of articles.

The mapped articles within urban management research have a moderately distinct divide between clusters that focus on basic, fundamental research, and those that synthesize/append that data for application. Authors that were present in more than one cluster were published in different journals that demonstrated a change of focus to international application or spatial technology use. This divide suggests that the urban emissions research community is well-connected across sub-disciplines, and that individual researchers conduct variable research within the same body of published work.

Discussion

While other education institutions, particularly those in areas with commercial timber opportunities, have embraced monitoring their land for changes in ecological or potential economic value, it is still uncommon for carbon and pollution benefits to be included in any potential project evaluation. This knowledge can help a landholding institution make more informed and sustainable choices, as well as to integrate the benefit of Emory's forests into its greenhouse gas and offset reports. Emory's forests store 50,510 tons of carbon (valued at $1.826 million) and sequester 2,318 tons annually, with an annual increase as trees mature and grow. These results indicate that this base would rapidly increase with the addition of immature hardwood tree species as saplings and retain that carbon once grown. For example, University of North Carolina- Chapel Hill, defined and sampled areas of its campus land and sections of private forest near its campus using I-Tree Eco to gather estimates, finding that increasing the density of forests could significantly increase the potential storage and annual sequestration of the campus and adjacent land (Clay 2012). University of Georgia has adopted design standards based off repeated monitoring of campus forest system, including green roof guidelines, integrated green space, and restriction of annual planting beds that demonstrate a successful integration of monitoring and valuation as an example for Emory to follow (Office of University Architects UGA 2016).

While Emory works specifically to preserve a core of campus buildings and designate land for non-development use, urban land and opportunities for expansion are quickly becoming scarce. The University's main campus, as defined by the initial tree inventory, is approximately 61.8% building roof cover/impervious surface and 38.2% naturally-developed space such as lawn or tree canopy. As Emory University already has a demonstrated commitment to its campus trees, it could distinguish itself as a leader in sustainable development and campus management by 1) establishing annual protocols for ecosystem services monitoring, 2) reviewing its campus ecosystem and 3) working to propose changes to increase aesthetic quality and ecological functionality in tandem. Emory’s actions on building energy use and campus waste management already position the university as an institution willing to take substantial action to decrease its emissions. Further managing for carbon storage and sequestration, native species choice, campus aesthetics, air quality, and ecological resilience can assist Emory in maintaining and expanding its forest system as a considerable asset to the community.

Main campus recommendations

Eco is a useful tool for repeated and consistent monitoring. As a prerequisite for managing for these benefits, my first recommendation for Emory’s natural land management is that 1) Emory adopt the use of Eco for main campus trees and Canopy for forest estimates and 2) use a biannual estimate as a reported offset in Emory’s University-wide greenhouse gas inventory. Thirdly, I recommend the University avoid planting large numbers of new trees as street trees and work as much as possible to recreate forest conditions (understory of plants, density, and diversity of species).

Trees that were cut in forest conditions should be replaced in similar conditions as much as possible. While many of Emory’s street trees are Japanese Zelkova (Zelkova serrata), which has a high sequestration rate and stress tolerance, transitioning our planting away from street medians and tree lines to naturalistic conditions would increase long-term carbon storage, allow an increase in species diversity, and ensure trees planted for replacement can reach a substantial size. Integration of ecosystem services that cannot be valued by humans, including the inherent ecological value of the system to its wildlife, could help facilitate this transition. Increasing the presence of large, productive tree species in forested conditions such as Loblolly Pine (*Pinus taeda*), White Oak (*Quercus alba*), Water Oak (*Quercus nigra*), and Pecan (*Carya illinoinenis*), along with protecting existing areas of greenspace from development can further work to offset

Emory’s total greenhouse gas emissions, I recommend an expansion of Emory’s upper canopy as well as an increase in the density of campus trees.

Native species expansion and management

In support of these main recommendations to support measurable ecosystem services on campus, smaller actions that change annual habits can be optimized for ecological benefit. Stated as a university-wide goal within its Sustainability Vision Statement, transitioning to completely native landscaping would increase the biodiversity and general resilience of the campus ecosystem, but would be a difficult undertaking. While no timeline or mechanism for implementation was included in the vision, a system of progressively increasing yearly requirements on the percentage of landscaping purchases of non-invasive or native plants would potentially finalize campus vegetative development as naturally and sustainably integrated.

Species that are not yet prominent on campus but have native ecological and aesthetic value should be further integrated into the campus ecosystem for their holistic and functional values (e.g., Shortleaf Pine (*Pinus echinata*), Southern Red Oak (*Quercus falcata*), Swamp Chestnut Oak (*Quercus michauxii*), each with less than 3 individuals identified in the inventory). The City of Atlanta provides a native and non-invasive tree planting list, including possible combinations of overstory, midstory, and underscore-size species to increase diversity and vegetation density (City of Atlanta Arborist Division 2015). Further integration of prominent tree species such as White Oak, Water Oak, and Pecan increases pedestrian shade, overall stored carbon, structural value, and diversity of the native tree canopy, all while increasing the aesthetic beauty of protected campus areas.

Among the other categories of vegetation on Emory’s campus, Emory could further benefit by transitioning as much of the remaining campus area planted in annuals (a small but visually prominent portion), landscaping pine straw, and lawn as possible to: perennial landscaped plants, wildflowers, non-invasive low-light tolerant groundcover and mixed-meadow lawn.

Pine straw cover within vegetation beds represents an additional untapped area for potential perennial vegetation expansion. Species similar to Creeping Phlox (*Phlox subulata*), Allegheny spurge (*Pachysandra procumbens*), and Partridgeberry (*Mitchella repens*) would compete with invasive ivy and add visual diversity to areas of groundcover. Any conversion of this pine straw from a previously unvegetated area into vegetative cover increases the carbon sequestration potential of Emory's campus and decrease emissions from decomposing pine straw while adding to the ecological health of the campus ecosystem. This transition also facilitates a larger move to replace the presence of invasive English Ivy (*Hedera helix*) and ornamental plants with functional replacement species that would further confirm Emory's commitment to campus ecosystem functionality.

Campus sustainability vision and aesthetic management

The recommendations for Emory's management of its on-campus vegetation align with Emory's institutional goal of a "campus within a forest"; a phrase descriptive of the natural design of Emory's historical Atlanta campus and a guiding principle for future campus development (Emory Sustainability Vision 2016). Ecological management and aesthetic value share in this priority at Emory, as demonstrated by the active and visible Office of Sustainability Initiatives and Green Building design guidelines, but increasing ecological benefits while maintaining campus aesthetics could potentially distinguish Emory as a university for prospective students interested sustainable business and sciences. As a destination university for those engaging in multidisciplinary research, Emory produces admissions literature and advertises its campus's natural amenities to attract business, students, faculty, and staff through campus visits and virtual tours.

At the simplest level, an increase in total tree cover on main campus would increase pedestrian shade, sequester and store an increased amount of carbon, decrease stormwater runoff, and contribute to the University's goal of planting 200 trees in the next decade. If monitoring was integrated into annual greenhouse gas inventories as an offset, Emory could assess and maintain that offset in a simple way by including in campus reporting via The Association for the Advancement of Sustainability in Higher Education guidelines (Barnes 2009). Stormwater management, energy savings, and emissions/pollution reduction are all stated goals in Emory's sustainability vision that could be monitored and managed with the assistance of a reliable and easy-to-use estimation tool like Eco or Canopy.

Air quality and pollution abatement recommendations

Emory also could benefit from emissions monitoring and biomass expansion due to its extensive healthcare network and facilities. Pollution abatement values, particularly decreases in O_3 and particulate matter, symbolize decreased probability of costly treatment for those with associated health conditions, and ultimately could result in significant cost savings across the system as a whole. Emory has already taken substantial on-campus measures to make its property a "healing" environment adjacent to Children's Healthcare of Atlanta through such actions as designating itself a Tobacco-Free campus and attempting to alleviate standing traffic on Clifton road with infrastructure expansions. I-Tree Eco and Canopy estimate that the Emory's forests areas alone remove 2.52 tons of PM 10 air pollution, 10.44 tons of ozone (O_3), and 1.2 tons of nitrogen dioxide (NO_2) annually, contributing to better air quality and potentially health outcomes than in areas without urban trees. Emory could further improve its healing environment by increasing the total number of campus trees, particularly in those areas nearest to Children's Healthcare of Atlanta and the Emory rehabilitation facilities on Clifton road to assist in air pollution removal and general aesthetic value.

Campus resilience and future development

The adoption of Eco as an evaluation tool could help Emory monitor the health and annual benefits of its ecosystem without placing significant stresses on an already overtaxed employee base. Eco helps projects represent their benefits in a way that all parties in the proposal process can decide and consider in an informed fashion. For example, a reforestation project that wants to transition a large lawn into a demonstration forest could approximate benefits by appending the baseline campus tree inventory in Eco with the associated physical data for the new trees. Generating a report would demonstrate a minimum amount of benefit for the project, only to compound and increase annually. These benefits could be used to advocate for alternative land use projects for areas that may be developed in the future.

Another demonstration benefit of Eco, which could assist Campus Services, is the projection feature that uses death and growth rates and scheduled plantings to create an estimate of future forest size, health, and future ecosystem benefit rates for a set number of years. Smaller campuses may not need to monitor a multitude of ecosystem services in detail and could benefit from using a remote sensing estimation tool such as Canopy.

Emory’s main campus and forested land boasts a combined structural value of over 3 million dollars, not including annual, active, or associated benefits like carbon storage. Structural or replacement value estimates indicate the amount of money it would take to replace a specific tree or area, if even physically possible. Displaying a high structural value gives an explicit monetary value to Emory’s highly-regarded urban forests and adds a further incentive to keep them intact, functional, and healthy. Additionally, demonstrating and factoring in the lost value when trees are to be cleared for construction could lend itself to a more informed and sustainable university development plan. While this thesis worked to extensively evaluate the added benefit of ecosystem services from an emboldened natural university environment, associated social benefits of positive community reputation and representation were not considered and would likely further increase the value of these areas. Emory's forested land constitute both present and potential benefits for current/prospective community members, sustainability leadership, and healthcare partners with the university system at large.

Conclusion

A growing set of urban and climatic concerns may soon begin to define human lives in developed nations through increased incidences of chronic disease; however, it is possible that our collective relief could be sought through concrete and sustainable actions that invest in critical natural systems for humankind's health and wellbeing. Nationwide, urban and residential forests account for billions of dollars in annual cost savings and encompass an impressive amount of secondary ecological and social benefits. On a smaller-scale, Emory's campus trees can reduce costs and increase the environmental quality of campus areas. I choose various estimation tools and methods, completed a comprehensive carbon inventory of Emory University, and used those estimates along with stated Emory University goals to recommend future actions that stand to benefit both the university community and to the overall green space in Atlanta.

The ability of scientists and managers to communicate best practices and exchange empirical knowledge is often hindered by lack of shared communication, goals, or processes. By incorporating this user-end technology, a manager that does not have data processing/modeling experience can easily and readily describe their system in a multitude of new ways. This thesis sought to convey the experience of these tools and their applications by describing the completion of an inventory and recommending actions based the results. Future priorities should work to apply technology (GIS, I-Tree Tools, etc.) to existing datasets, as well as further define the differences between natural and urban forests. These systems can be monitored and managed for mutual human and ecosystem benefits as human motivation and urban ecological knowledge increases.

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Tables and Figures

Table 1. Standards and considerations for choice of software tool

Consideration	Question
“User-Friendly”	How familiar must a user be with general mid-level software (statistics, data manipulation, graphics) to comfortably and readily use the tool?
Time/Labor Investment	Does the tool require data from field work to report or remote data such as GIS or satellite imagery? How long does the process of completing an estimate take?
Format of Input Data	Can previously collected data be imported? Does the tool accept multiple common formats or need a specific conversion process?
Accessibility/Cost	How is the software distributed? Does a user need an academic or organizational affiliation to access the tool?
Flexibility of Analysis	What type(s) of results can be generated with the data collected? Are predictive capabilities available?
Fitting Institutional Needs	What other attributes unique to the tool make it specifically suitable to Emory University?

Table 2. Other estimation tools and their suitability for Emory's urban canopy

Method	Input	Output	Reasons for Exclusion/Inclusion
FORCARB2 (Non-Urban, Freely accessible)[1]	Data on timber stocks, death, health, and annual growth provided by monitoring system ATLAS	Total forest carbon stock and area change estimates on 5-year interval, outputs can only be specific to a state, region, or nation, not user-selected areas	• Not specific to urban areas • Variable available analyses, but all with a focus on forest products and long-term change • Software required manual installation and modification of code, not suitable for average management employee
GCOLE3[2]	Select a study area and retrieves available datasets on forest composition and species from existing plots including species dominance and carbon estimates	Does not generate estimates Allows the user to view the collected carbon reports from previous ground-level estimates	• Not specific to urban areas • Does not generate an estimate of carbon, or other ecosystem services. • Interface difficult to navigate, documentation is scarce
NC Carbon Calculator[3]	Number of trees in selected area, size of trees, square area of turfgrass, transportation information related to car emissions (optional)	Estimates of carbon storage by trees and lawn. Estimations of carbon emissions on a home or small business level	• Specific to very small scale projects, suitable for a single residence or single building within a campus • Tree carbon estimates do not include the effects of species difference, tree health, or light exposure, limiting their reliability. • Insufficient accessible methodology to use these estimates for management decisions
EPA Carbon Sequestration Worksheet[4]	Physical data on land and trees, including year when each tree was planted, species, and age of tree. Worksheet then guides an estimate of carbon	Estimates of carbon sequestration and stored carbon.	• Need to know age of tree and year planted, making estimates impossible for institutions with missing or incomplete records • Tree carbon estimates do not include the effects of species, tree health, or light exposure, limiting their reliability

	processes on campus		

Table 2. Continued, Industry tools and their suitability for Emory’s urban canopy

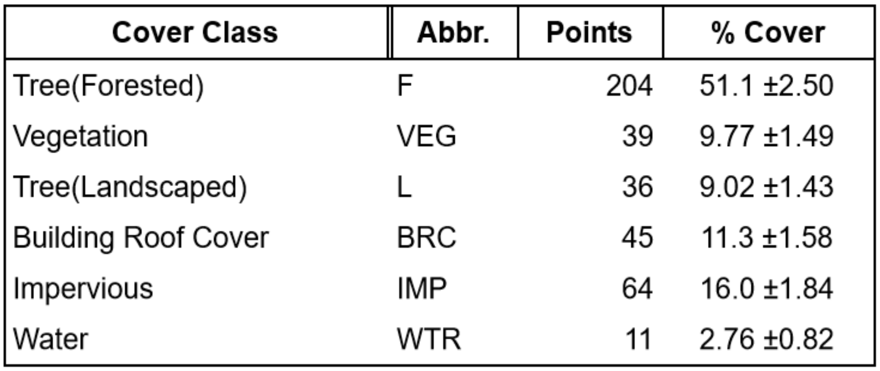
Method	Input	Output	Reasons for Exclusion/Inclusion
I-Tree Tools – ECO and CANOPY[5]	ECO - Tree data (species, crown size/health, tree height and diameter, light exposure, etc.) CANOPY – A polygon of area selected on satellite imagery and images from that area as data points.	ECO – Estimates of carbon sequestration and stored carbon, estimates of avoided runoff, pollution abatement, and pest management. CANOPY – estimates of tree cover and associated tree benefits including carbon sequestration/ storage and pollution removal	• Specific methodology available for all aspects of model • Specific to urban areas • Created from campus-level or institution level analyses • Ability to produce professional figures and a variety of results, centered around but not limited to carbon estimates. • Accessible, both Eco and Canopy require little to no background knowledge to produce estimates

[1] - https://www.nrs.fs.fed.us/pubs/35613
[2] - http://www.ncasi2.org/GCOLE3/gcole.shtml
[3] - http://www.carboncalculator.ncsu.edu/Trees.aspx
[4] - https://www3.epa.gov/climatechange/Downloads/method-calculating-carbon-sequestration-trees-urban-and-suburban-settings.pdf
[5] - http://www.itreetools.org/

Table 3. I-Tree Eco V.6 Inventory Variables and Data Types	
Variable	**Data Formatting**
DBH*	Number (m)
Species*	Species common name in or added to Eco database
Tree ID	Tag Number (unique identifier, integer)
Height of DBH Measurement	1.4m (Eco supports 0.1 to 6m) (USDA Forest Service 2017)
Total Tree Height	Number (m)
Crown Size	Number (m) and percentage (Height to live top, Height to Crown base, Width, Percent Missing)
Direction to Building, Distance to Building	Direction: 1 to 360, Distance: 0.1 to 60
Crown Light Exposure	1 - 5 (how many sides of 5 are fully exposed to light)

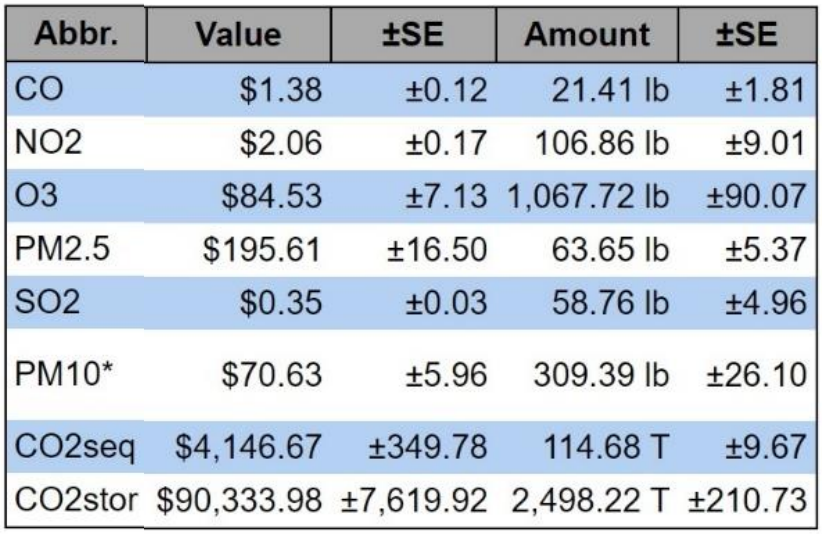
*- indicates field required by Eco

Table 4. Percent groundcover by category for full property using Canopy

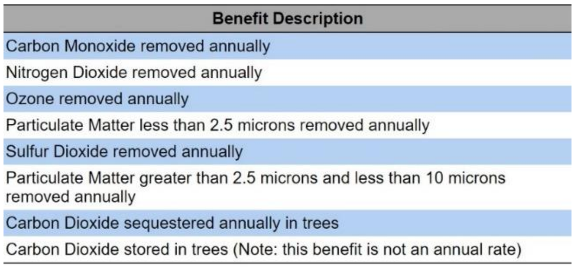


Cover Class	Abbr.	Points	% Cover
Tree(Forested)	F	204	51.1 ±2.50
Vegetation	VEG	39	9.77 ±1.49
Tree(Landscaped)	L	36	9.02 ±1.43
Building Roof Cover	BRC	45	11.3 ±1.58
Impervious	IMP	64	16.0 ±1.84
Water	WTR	11	2.76 ±0.82

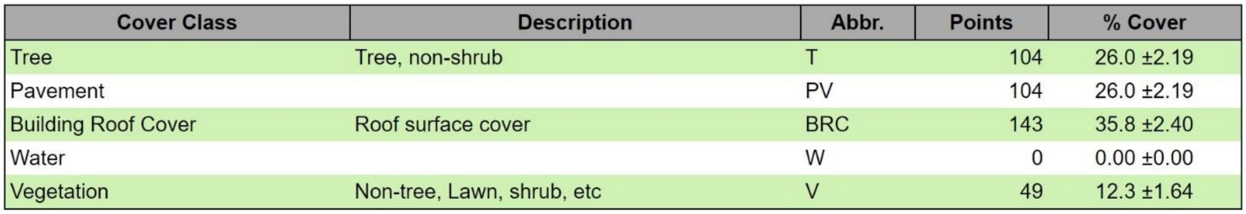
Table 5. Percent groundcover and associated benefits for main campus using Canopy



Abbr.	Value	±SE	Amount	±SE
CO	$1.38	±0.12	21.41 lb	±1.81
NO2	$2.06	±0.17	106.86 lb	±9.01
O3	$84.53	±7.13	1,067.72 lb	±90.07
PM2.5	$195.61	±16.50	63.65 lb	±5.37
SO2	$0.35	±0.03	58.76 lb	±4.96
PM10*	$70.63	±5.96	309.39 lb	±26.10
CO2seq	$4,146.67	±349.78	114.68 T	±9.67
CO2stor	$90,333.98	±7,619.92	2,498.22 T	±210.73

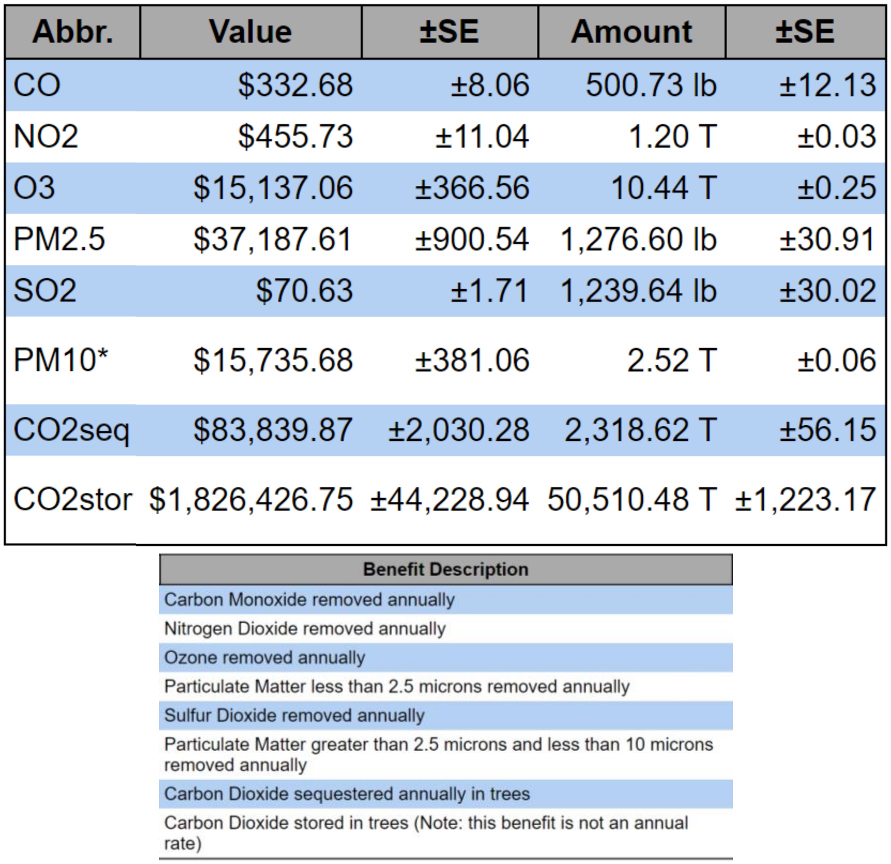


Benefit Description
Carbon Monoxide removed annually
Nitrogen Dioxide removed annually
Ozone removed annually
Particulate Matter less than 2.5 microns removed annually
Sulfur Dioxide removed annually
Particulate Matter greater than 2.5 microns and less than 10 microns removed annually
Carbon Dioxide sequestered annually in trees
Carbon Dioxide stored in trees (Note: this benefit is not an annual rate)



Cover Class	Description	Abbr.	Points	% Cover
Tree	Tree, non-shrub	T	104	26.0 ±2.19
Pavement		PV	104	26.0 ±2.19
Building Roof Cover	Roof surface cover	BRC	143	35.8 ±2.40
Water		W	0	0.00 ±0.00
Vegetation	Non-tree, Lawn, shrub, etc	V	49	12.3 ±1.64

Table 6. Urban tree benefits, Emory forested areas using Canopy



Abbr.	Value	±SE	Amount	±SE
CO	$332.68	±8.06	500.73 lb	±12.13
NO2	$455.73	±11.04	1.20 T	±0.03
O3	$15,137.06	±366.56	10.44 T	±0.25
PM2.5	$37,187.61	±900.54	1,276.60 lb	±30.91
SO2	$70.63	±1.71	1,239.64 lb	±30.02
PM10*	$15,735.68	±381.06	2.52 T	±0.06
CO2seq	$83,839.87	±2,030.28	2,318.62 T	±56.15
CO2stor	$1,826,426.75	±44,228.94	50,510.48 T	±1,223.17

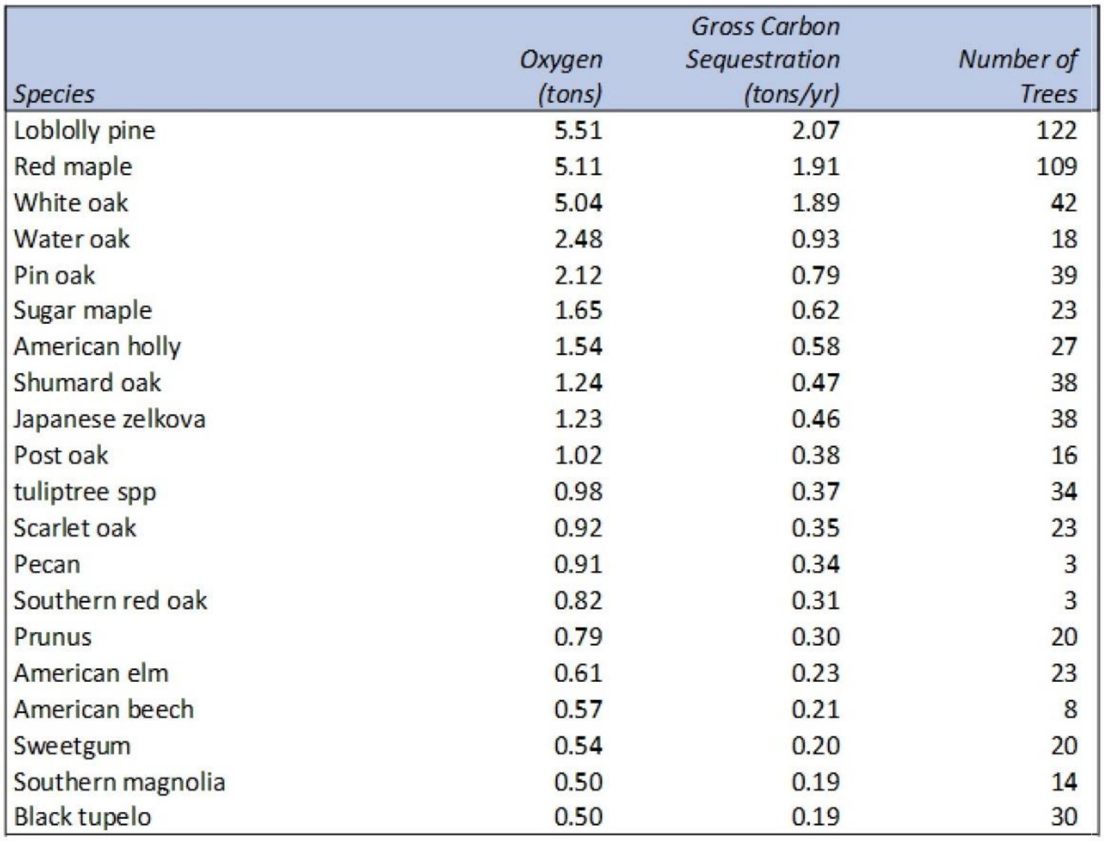
Benefit Description
Carbon Monoxide removed annually
Nitrogen Dioxide removed annually
Ozone removed annually
Particulate Matter less than 2.5 microns removed annually
Sulfur Dioxide removed annually
Particulate Matter greater than 2.5 microns and less than 10 microns removed annually
Carbon Dioxide sequestered annually in trees
Carbon Dioxide stored in trees (Note: this benefit is not an annual rate)

Table 7. Comparative I-Tree Eco, Canopy, and ArborGuard results summary

Estimation Method	Storage (Ton)	Sequestration (Tons/year)	Avoided Runoff (cubic feet/year)	Pollution Removal (tons/year)	Structural Value ($)
1. ARBORGUARD	327.6	11.2	---	0.707 tons/year	$1.67 mil
1. ECO (887 Trees)	355 ($47,300)	15 ($2,200)	31,970 ($2,140)	0.391 tons/year ($3,090)	$1.64 mil
2. CANOPY (Same defined area as ECO and AG)	2,498.2 ($90,333)	114.68 ($4,146)	---	0.738 tons/year ($354.56)	---
3. CANOPY (Only Lullwater Preserve, Hahn Woods, Baker Woodlands)	50,510 ($1.83 mil)	2,318 ($83,839)	---	17.176 tons/year ($68,919.39)	---
4. ECO + CANOPY (887 Trees + Forested Property)	50,865 ($1.87 mil)	2,333 ($86,039)	31,970 ($2,140)	17.529 tons/year ($71,479.39)	>$3.47 mil*

*-Structural value for ECO + CANOPY is the sum of the ascribed structural value from ECO and the monetary value of carbon storage from CANOPY for forested property. Actual structural value is much higher than functional value (carbon storage) as it is derived from the replacement cost of the forest.

Table 8. Annual oxygen production by species using Eco



Species	*Oxygen (tons)*	*Gross Carbon Sequestration (tons/yr)*	*Number of Trees*
Loblolly pine	5.51	2.07	122
Red maple	5.11	1.91	109
White oak	5.04	1.89	42
Water oak	2.48	0.93	18
Pin oak	2.12	0.79	39
Sugar maple	1.65	0.62	23
American holly	1.54	0.58	27
Shumard oak	1.24	0.47	38
Japanese zelkova	1.23	0.46	38
Post oak	1.02	0.38	16
tuliptree spp	0.98	0.37	34
Scarlet oak	0.92	0.35	23
Pecan	0.91	0.34	3
Southern red oak	0.82	0.31	3
Prunus	0.79	0.30	20
American elm	0.61	0.23	23
American beech	0.57	0.21	8
Sweetgum	0.54	0.20	20
Southern magnolia	0.50	0.19	14
Black tupelo	0.50	0.19	30

Figure 1. Emory University Main Campus, ArborGuard

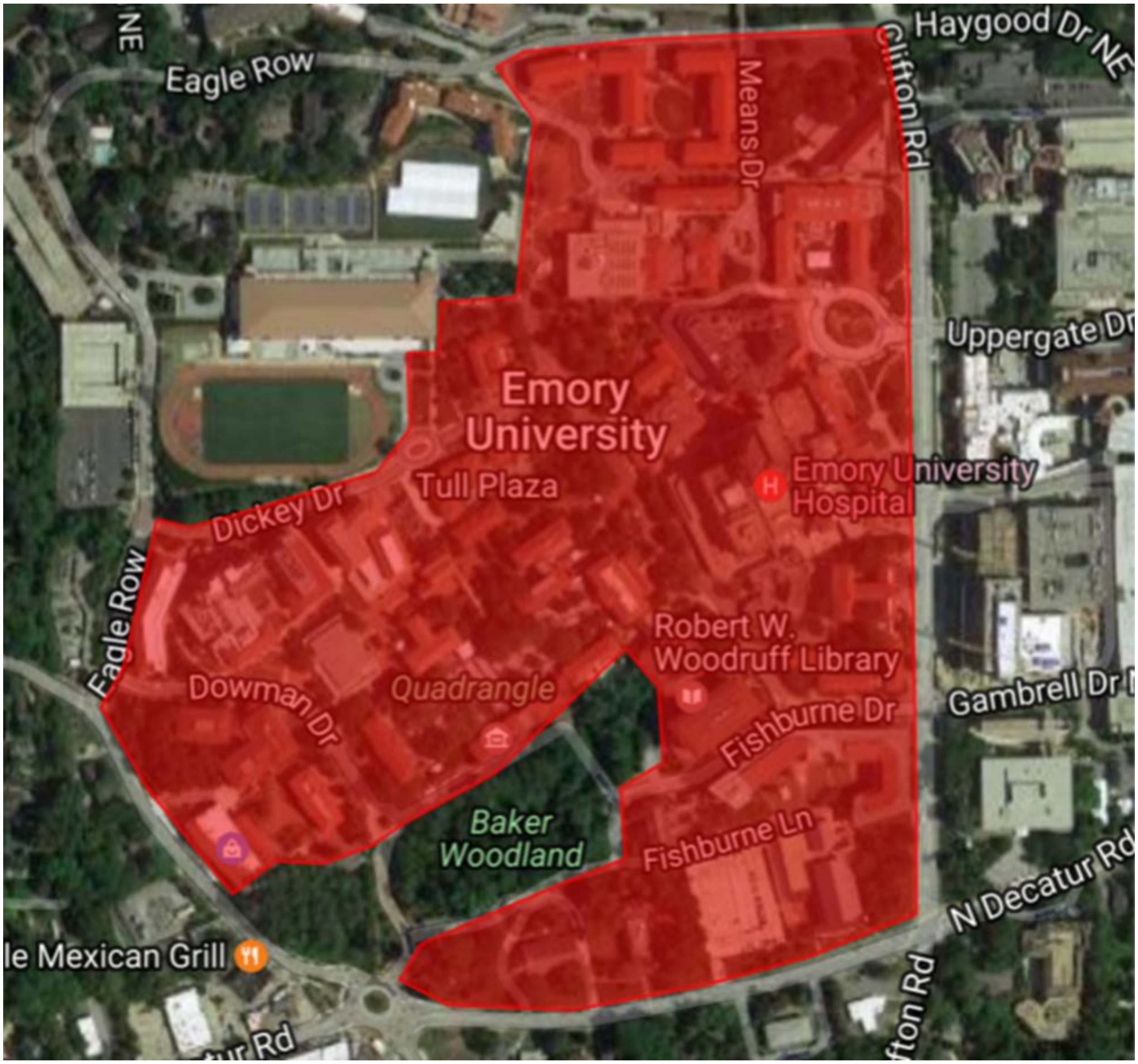


Figure 2. Emory University Forested Areas measured by Canopy

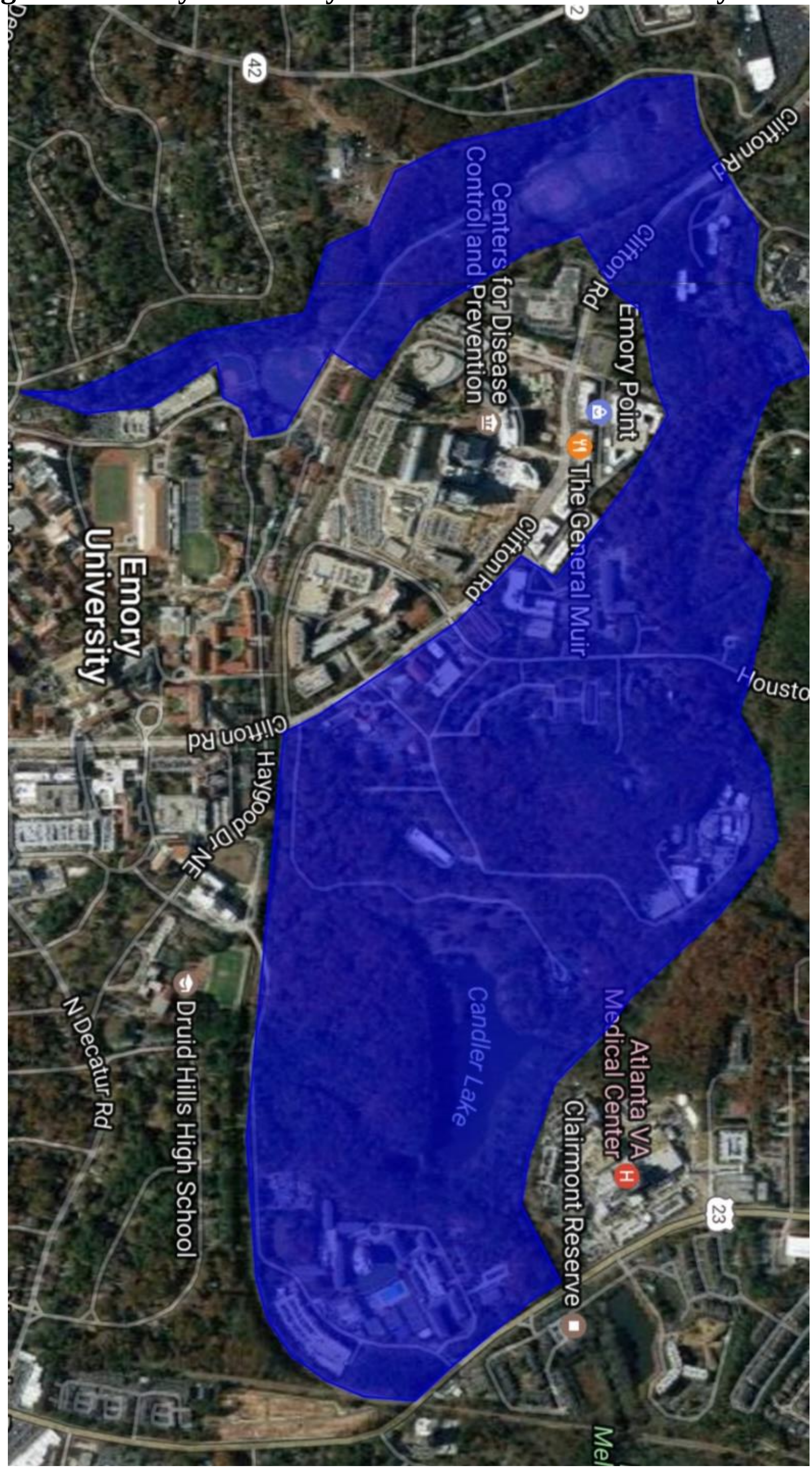


Figure 3. Carbon storage: amount (points) and value (bars) from Eco

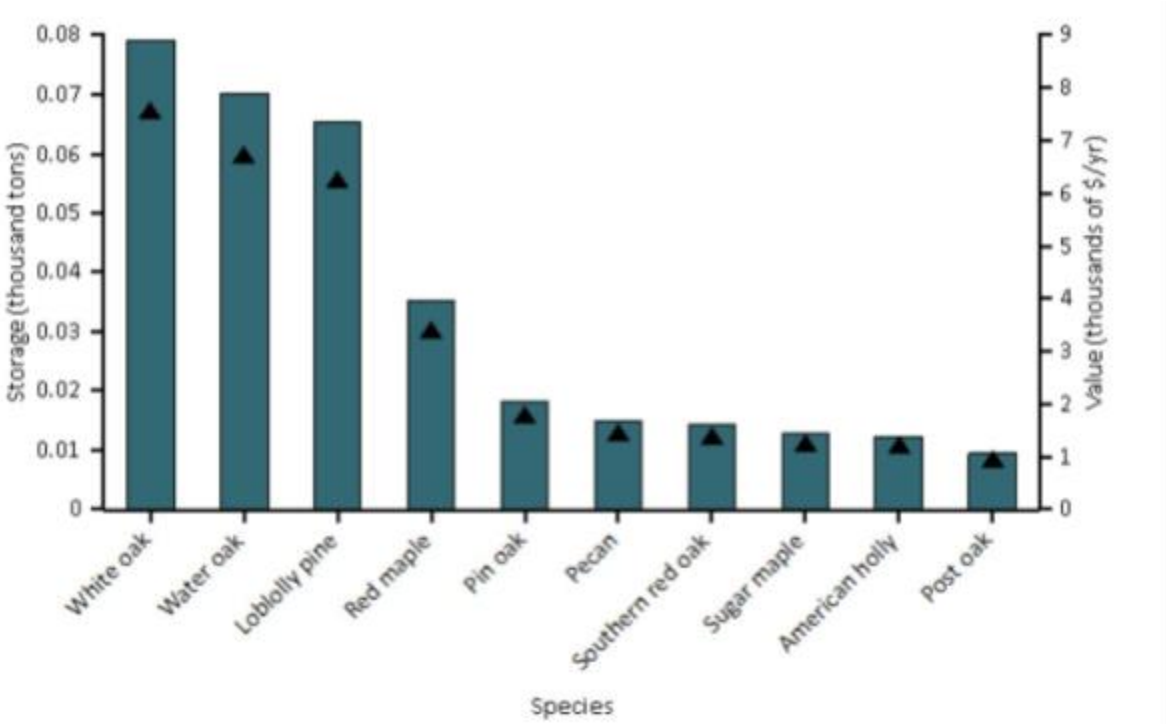


Figure 4. Annual gross carbon sequestration: amount (points) and value (bars) from Eco

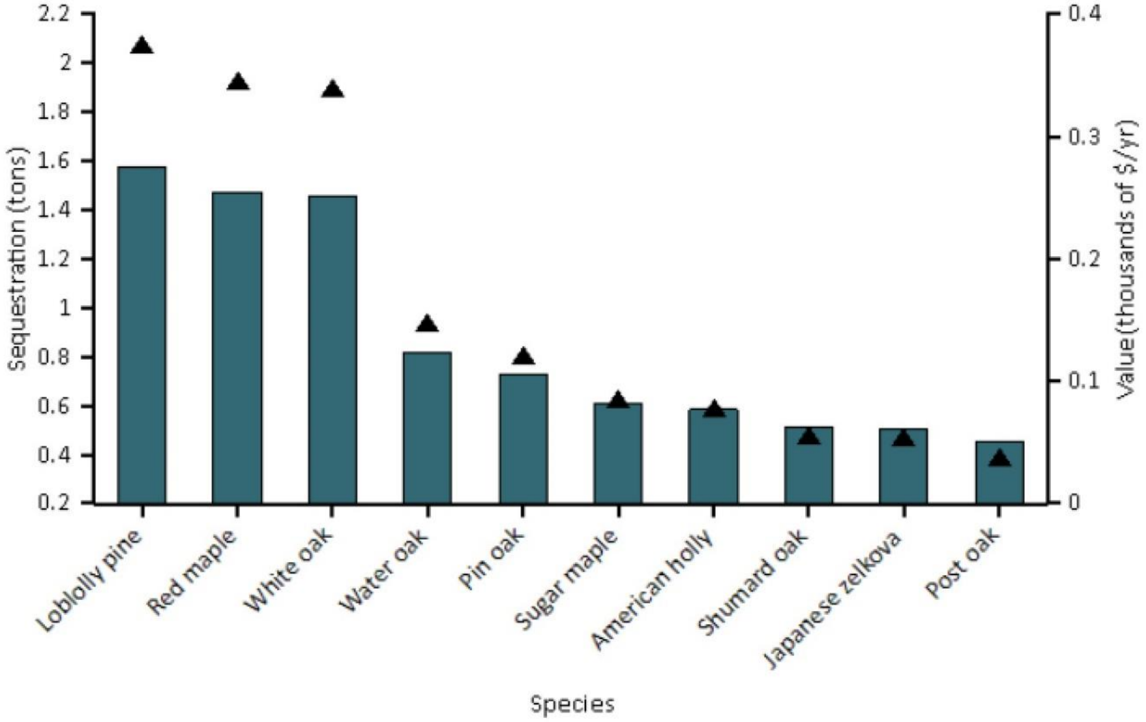


Figure 5. Annual pollution removal by individual pollutants (points) and associated benefit (bars) from Eco

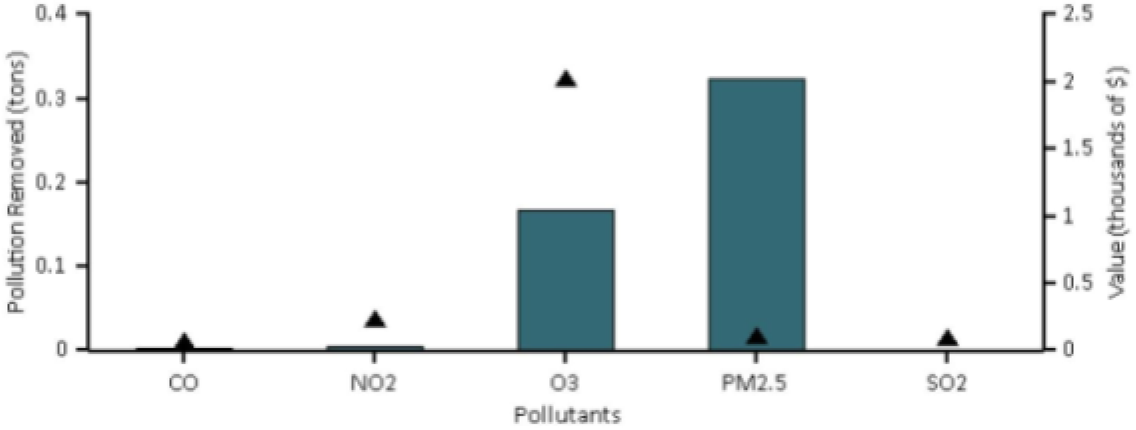


Figure 6. Annual avoided runoff (points) and associated value (bars) from Eco

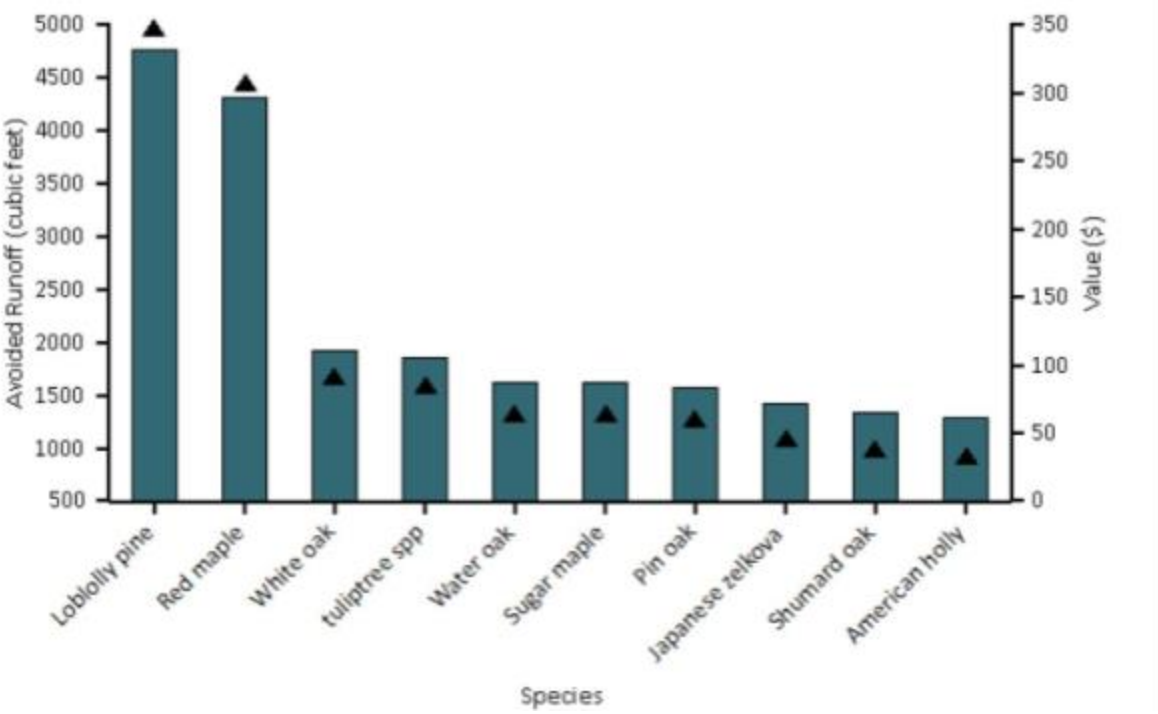
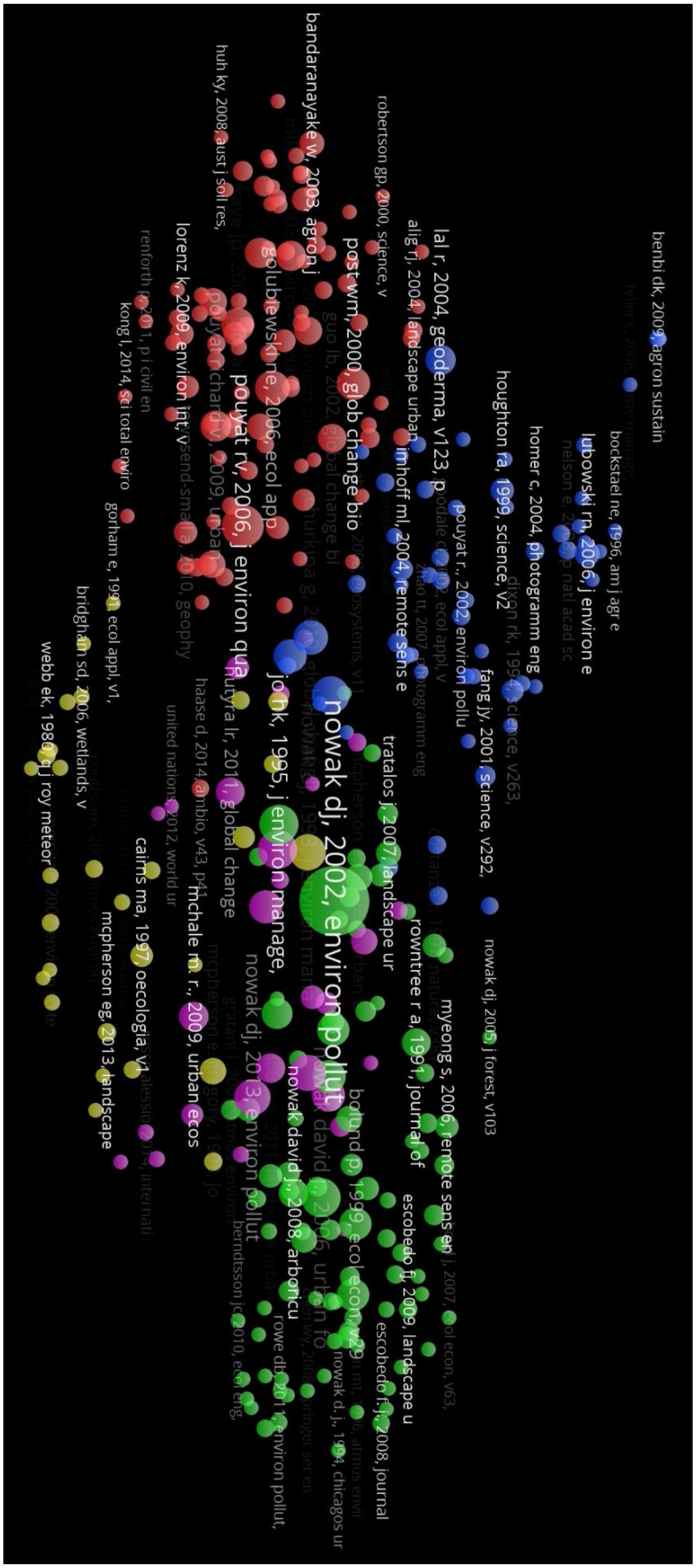


Figure 7. VOS Viewer Map Image



Appendix 1.1 – I-Tree Eco Methodology, UFORE A, B, and C

A – Anatomy of the Urban Forest

- Field data is used in regression equations to calculate leaf area for deciduous urban species (Nowak 1996), using genus or hardwood averages when species-specific data was unavailable.
- Pine and conifer leaf area was calculated with adjusted equations from the same source.
- Biomass was derived from converting leaf area with species-specific measurements of g leaf dry weight/m^2 of leaf area.
- A plot competition factor (PCF) was included to account for overlapping tree crowns when location data is collected.
- Structural value, or compensatory value, is based on trunk area, species, condition, location, and values from the Council of Tree and Landscape Appraisers (1992) and International Society of Arboriculture for transplant cost.

B – Biogenic Volatile Organic Compound (VOC) Emissions

- UFORE-B estimates the hourly emission of isoprene (C5H8), monoterpenes (C10 terpenoids), and other volatile organic compounds (OVOC) by multiplying leaf biomass by genus-specific emission factors (Nowak et al, 2002) to produce emission levels standardized to 30C, photosynthetically active radiation (PAR) flux of 1,000 µmol m-2 s-1.
- Standardized emissions are converted to actual emissions based on light/temperature correction factors (Geron et al. 1994) and local meteorological data. Extensive equations are found in the full UFORE methodology (UFORE Model Description and Methodology 2003)

C – Carbon Storage and Sequestration

- Biomass for each measured tree was calculated using allometric equations; As deciduous trees drop their leaves annually, only carbon stored in wood biomass was calculated for these trees. Total tree dry-weight biomass was converted to total stored carbon by multiplying by 0.5 (Forest Products Lab, 1952; Chow and Rolfe 1989).
- To estimate monetary value associated with urban tree carbon storage and sequestration, carbon values were multiplied by $20.3/tC based on the estimated marginal social costs of carbon dioxide emissions (Fankhauser, 1994).
- Average diameter growth from the appropriate land-use and diameter class was added to the existing tree diameter (year x) to estimate tree diameter in year x+1.
- Adjustment factors were based on percent crown dieback and the assumption that less than 25-percent crown dieback had a limited effect on d.b.h. growth rates.
- The difference in estimates of C storage between year x and year x+1 is the gross amount of C sequestered annually
- Individual tree estimates of mortality probability/decomposition rates were aggregated upward to yield total estimates of decomposition for the tree population. The amount of carbon sequestered due to tree growth was reduced by the amount lost due to tree mortality to estimate the net carbon sequestration rate.

Appendix 1.2 - I-Tree Eco Methodology, UFORE D and E

D – Dry Deposition of Air Pollution

- In UFORE-D, the pollutant flux (F; in g m -2 s-1) is calculated as the product of the deposition velocity (V_d; in m s-1) and the pollutant concentration (C; in g m-3): $F = V_d \times C$
- Deposition velocity is calculated as the inverse of the sum of the aerodynamic (R_a), quasilaminar boundary layer (R_b) and canopy (R_c) resistances: $V_d = (R_a + R_b + R_c)^{-1}$
- Hourly meteorological data from the closest weather station (usually airport weather stations) were used in estimating Ra and Rb. The aerodynamic resistance is calculated as: $R_a = u(z) \times u_*^{-2}$, where u(z) is the mean windspeed at height z (m s-1) and u* is the friction velocity (m s-1).
- Extensive equations and descriptions of constants, etc. are found in the full UFORE methodology.
- The ability of individual trees to remove pollutants was estimated for each diameter class using the formula (Nowak 1994c): $I_x = R_t \, x \, (LA_x / LA_t) / N_x$, where I_x = pollution removal by individual trees in diameter class x (kg/tree); R_t = total pollution removed for all diameter classes (kg); LA_x = total leaf area in diameter class x (m2); LA_t = total leaf area of all diameter classes (m2); and N_x = number of trees in diameter class x. This formula yields an estimate of pollution removal by individual trees based on leaf surface area (the major surface for pollutant removal).

E – Energy Conservation

- Using the tree size, distance, direction to building, climate region, leaf type (deciduous or evergreen) and percent cover of buildings and trees on the plot, the amount of carbon avoided from power plants due to the presence of trees was calculated based on methods in McPherson and Simpson (1999).
- The amount of carbon avoided was categorized into the amount of MWh (cooling), and MBtus and MWh (heating) avoided due to tree energy effects.
- To determine the estimated economic impact of the change in building energy use, state average price per kWh between 1970 and 2002 (Energy Information Administration, 2003a) and per MBtu for natural gas, residential fuel, and wood between 1990 and 2002 (Energy Information Administration, 2003b-f) were used.
- All prices were adjusted to 2002 dollars using the consumer price index (U.S. Department of Labor and Statistics, 2003).
- State prices were used to determine the value of energy effects. Average price for heating change due to trees was based on the average distribution of buildings in the region that heat by natural gas, fuel oil, and other (including wood) (McPherson and Simpson, 1999).

Appendix 1.3 – I- Tree Canopy Technical Notes - General

This tool randomly lays points (number determined by the user) onto Google Earth imagery and the user then classifies what cover class each point falls upon. The user can define any cover classes that they like and the program will show estimation results throughout the interpretation process. Point data and results can be exported for use in other programs if desired. There are three steps to this analysis:

1) Import a file that delimits the boundary of your area of analysis (e.g., city boundary). Some standard boundary files for the US can be located on the US Census website. Data from these sites will require some minor processing in GIS software to select and export a specific boundary area polygon.

2) Name the cover classes you want to classify (e.g., tree, grass, building). Tree and Non- Tree are the default classes given, but can be easily changed.

3) Start classifying each point: points will be located randomly within your boundary file. For each point, the user selects from a dropdown list the class from step 2 that the point falls upon. The more points that are interpreted, the more accurate the estimate.

Limitations: The accuracy of the analysis depends upon the ability of the user to correctly classify each point into its correct class. The classes that are chosen for analysis must be able to be interpreted from an aerial image. As the number of points increase, the precision of the estimate will increase as the standard error of the estimate will decrease. If too few points are classified, the standard error will be too high to have any real certainty of the estimate. Information on calculating standard errors can be found below. Another limitation of this process is that the Google imagery may be difficult to interpret in all areas due to relatively poor image resolution (e.g., image pixel size), environmental factors, or poor image quality.

Calculating Standard Error and Confidence Intervals from Photo Interpreted Estimates of Tree Cover: In photo interpretation, randomly selected points are laid over aerial imagery and an interpreter classifies each point into a cover class (e.g., tree, building, water). With this classification of points, a statistical estimate of the amount or percent cover in each cover class can be calculated along with an estimate of uncertainty of the estimate (standard error (SE)). Based on the SE formula, SE is greatest when $p=0.5$ and least when p is very small or very large (Table 1).

Confidence Interval: In the case above, a 95% confidence interval can be calculated. “Under simple random sampling, a 95% confidence interval procedure has the interpretation that for 95% of the possible samples of size n, the interval covers the true value of the population mean” (Thompson 2002). The 95% confidence interval for the above example is between 30.1% and 35.9%. To calculate a 95% confidence interval (if $N>=30$) the SE x 1.96 (i.e., $0.0149 \times 1.96 = 0.029$) is added to and subtracted from the estimate (i.e., 0.33) to obtain the confidence interval.

SE if n < 10: If the number of points classified in a category (n) is less than 10, a different SE formula (Poisson) should be used as the normal approximation cannot be relied upon with a small sample size (<10) (Hodges and Lehmann, 1964). In this case: $SE = (\sqrt{n}) / N$

Appendix 1.4 - I-Tree Canopy Technical Notes – Air Pollution

- The air pollutants estimated are six criteria pollutants defined by the U.S. Environmental Protection Agency (EPA); carbon monoxide (CO), nitrogen dioxide (NO2), ozone (O3), sulfur dioxide (SO2), and particulate matter (PM), which includes particulate matter less than 2.5 microns (PM2.5) and particulate matter greater than 2.5 and less than 10 microns (PM10*).
- The default values (the multipliers) of air pollutant removal rates (g m-2 yr-1) and monetary values ($ m - 2 yr-1) for a unit tree cover were derived from i-Tree Eco analyses in the conterminous United States in 2010).
- These analyses were performed for rural and urban areas in all counties and then aggregated into the county-level values. i-Tree Canopy currently uses the county-level multipliers to estimate annual air pollutant removals and associated monetary values.

Air pollutant removals and concentration changes:

- Air pollutant removal and concentration change due to dry deposition to trees were estimated on an hourly-basis and then summarized for a year with i-Tree Eco.
- PM2.5 concentration was subtracted from the PM10 concentration to produce an adjusted PM10 concentration denoted as PM10* (2.5- to 10-micron particles) to avoid PM10 double counting PM2.5 values.

Air pollutant removal valuation:

- The U.S. EPA’s BenMAP was used to estimate the incidence of adverse health effects and associated monetary values resulting from changes in NO2, O3, PM2.5 and SO2 concentrations.
- The pollutant removal value for CO and PM10* were CO = $1,470 t-1 and PM10* = $6,910 t-1 for urban and CO = $27 t-1 and PM10* = $126 t -1 for rural areas.
- Urban values were estimated using national median externality values adjusted to 2010 values using the producer price index, while rural values were derived from urban values adjusted based on the rural to urban value ratio for all four BenMAP pollutants (NO2, O3, PM2.5, and SO2).
- For each rural and urban area in counties, calculated total removal amount and monetary value were divided by the area’s total tree cover to derive the removal amount and monetary value multipliers, respectively.
- In i-Tree Canopy, the air pollutant amount annually removed by trees and the associated monetary value can be calculated with the tree cover in the area of interest multiplied by these multipliers based on the county-level values in the United States.

Adverse effects of trees for PM2.5:

- Trees are a temporary retention site for atmospheric particles, PM2.5 intercepted by trees due to dry deposition may be resuspended to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall. In i-Tree Eco, PM2.5 is intercepted and accumulated on trees on an hourly basis with no rain or low wind conditions, typically resulting in decrease in the PM2.5 concentration.
- The PM2.5 accumulated on leaves is washed off from leaves to the ground with a rain event. When an hourly high wind event occurs, larger amount of accumulated PM2.5 than deposited in that hour may be resuspended to the atmosphere, typically causing increase in the PM2.5 concentration.
- The PM2.5 concentration can also be affected by the atmospheric mixing height: when the PM2.5 quantity remains the same in atmosphere, higher mixing height leads to lower concentration and vice versa. Because of these atmospheric factors the mean PM2.5 concentration may be increased annually or quarterly in areas with low rain and high winds throughout a year.