The University of Chicago

Campus Forest Analysis and Recommendations

AUGUST 2021

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The University of Chicago

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Executive Summary

The University of Chicago's 217-acre campus is home to 3,764 trees spanning 129 species, all maintained by Facilities Services. The University contracted Bartlett Tree Experts to conduct its third tree inventory and i-Tree Ecosystem Analysis in October of 2020; the results provide the framework for the following report. Ecosystem services (ES), while already provided by the campus forest, are not explicitly prioritized in current campus management practices; incorporation of ES will boost the functional value of the campus forest and provide numerous benefits to the campus and Hyde Park communities. Climate change poses an imminent threat to urban forest biodiversity and ES provision; management that incorporates climate projections is crucial in maintaining a thriving campus forest. The aim of this report is to combine current University tree management practices with a data-based analysis of campus forest properties and an extensive literature review of ecosystem services and climate change in order to develop actionable recommendations to strengthen the University of Chicago's campus forest.

This report begins with a section on tree ecosystem services (ES), which are the direct and indirect benefits trees provide to humans. Ten ES are overviewed based on an in-depth review of relevant literature: carbon storage/sequestration, air pollution mitigation, stormwater runoff management, urban microclimate regulation, building energy effects, noise attenuation, habitat provision and functions, human health benefits, aesthetic quality improvement, and oxygen production. This review is followed by a discussion of ES i-Tree quantification and the relative impacts of each ES on the University campus. We determine urban microclimate regulation, air pollution mitigation, building energy effects, habitat provision and functions, human health benefits, and aesthetic quality improvement to be the most impactful ES at the University of Chicago, while carbon storage/sequestration, stormwater management, noise attenuation, and oxygen production are deemed the least impactful ES. Ecosystem disservices and areas for future ES research are also included. Incorporating ES into University tree management practices will expand the benefits of campus trees and enhance the University's sustainability.

The second section discusses climate change and its impacts on campus trees, ES, USDA Plant Hardiness Zones, and pests and diseases. First, we summarize Chicago's past, present, and projected climate. Then, an overview of the limited literature discussing ES and climate change demonstrates that warm temperatures and increased nitrogen deposition are projected to initially increase tree growth, subsequently heightening ES provision. Around 2040-2070, researchers predict that water scarcity and prevalent extreme weather events will cause tree stress and mortality, leading to an overall decrease in ES provision by campus trees. A discussion of USDA Hardiness Zones details how cold fronts have shifted northward and will likely continue to migrate with climate change, rendering many currently thriving species maladapted to Chicago's climate but expanding other species' habitable ranges into the Chicago region. Section 2: Climate Change also covers that pest and disease prevalence is favored by warm temperatures and should be continually monitored to avoid campus tree outbreaks. The section covers the predicted effects of climate change on campus tree survival, as summarized in Table 5 in Section 2.4.1: Effects on UChicago Trees. Lastly, we discuss predicted effects on campus tree ES, as well as climate change evaluation techniques.

The third section focuses on succession planning and recommendations for campus forest management. It begins with a brief overview of ecosystem-based adaptation and the history of

UChicago's and Chicago's forest management practices. Using data from the 2020 i-Tree Ecosystem Analysis, Section 3: Succession Planning evaluates the campus forest age, condition, and species composition through maps and data visualizations, focusing on i-Tree "important" species and genera of interest to Facilities Services. The section then discusses the current factors considered in tree selection, such as budget, biodiversity, site exposure, and visual appeal before presenting a recommended, updated process for tree selection that incorporates ES and climate change factors. Finally, we present a table of future species for planting (Table 6 in Section 3.6.1: Future Species for Planting), as well as a synthesized list of management recommendations to sustain a healthy campus forest. The synthesized recommendations list is included below and in Section 3.7: Synthesized Recommendations for University Succession Planning. Implementation of these recommendations will increase the structural and functional values of the campus forest, in turn benefitting the campus and Hyde Park communities, local biodiversity, and the environment at large.

The final section discusses potential future areas of research building on the i-Tree Analysis and the information presented in this report. Ideas include energy/systems implications, human/psychological effects, and natural environment monitoring. All supplementary material is included in the three appendices.

Succession Planning Recommendations

1. Adoption of the updated flowchart for the tree planting process (Figure 13). This will ensure that forest climate change vulnerability and ecosystem services provision are accounted for in tree and site selection, thereby promoting ecosystem-based adaptation. (Sections 3.2, 3.6)

2. Further attribution of equal or greater significance to maintaining campus trees as to planting new trees. Fostering a healthy forest with low tree mortality rates will decrease carbon emissions and financial expenditures, as well as sustain ES. (Sections 3.4.1, Appendix A.1)

3. Explicit prioritization of biodiversity (ages, species, phenotypes, physiologies) at the species and forest scale. Areas of same-species groupings, as shown in Figure 11, should be addressed in site selections first, followed by areas of low diversity. Diversity establishes forest resiliency, a crucial component of ecosystem-based adaptation, and fosters both a more complex ecological system and a more visually appealing landscape. (Sections 1.3.2, 2.4.1, 3.2, 3.4.3, 3.5, 3.6.1, Appendix A.1, Appendix A.6, Appendix A.7, Appendix A.9)

4. Planting only tree species with plant hardiness zone ranges that include Chicago's current zones (5b-6a) and projected zones to 2099 (6a-7b) (as depicted in Table 4). Selecting species adapted to Chicago's present and future winter temperatures will decrease the likelihood of tree failure. (Sections 2.3.2, 2.4.1, 3.6)

5. Heightened assessment and amelioration of soil condition (nutrient levels, compaction, water content, etc.) prior to and after planting a tree. Poor soil quality is one of the primary causes of urban tree death and should remain a primary site consideration. (Sections 2.3.1, 2.4.1, 2.4.2, 3.5, 3.6.1, Appendix B.1, Appendix B.2)

6. Continued pest and disease monitoring (Emerald Ash Borer (*Agrilus planipennis*), Dutch Elm Disease, Oak Wilt, etc.) and avoided planting of pest-susceptible species (like some ashes (*Fraxinus*) and oaks (*Quercus*)). To prevent widespread tree infection and mortality, at-risk species should continue to be identified and not planted in clusters, although hybridized cultivars of such species can be favored. (Sections 2.3.3, 2.4.1, 2.4.3, 3.4.2, 3.4.3, 3.4.4, 3.5, 3.6.1, Appendix B.2)

7. Use of lower-energy tree planting and maintenance practices (handsaws and rakes instead of chainsaws and leaf blowers) when feasible. Such practices help prevent reaching the LPP (Last Positive Point), and thus allow individual trees to act as carbon sinks rather than carbon sources, improving the University's carbon footprint (Sections 2.4.1, 2.4.2, 3.4.2, Appendix A.1, Appendix B.1)

8. Incorporation of trees' ability to improve individual and community health (mental and physical) in site and species selections. Improved health is one of the primary services UChicago's campus trees provide to the community and is projected to become more impactful with climate change. (Sections 1.2, 1.3.2, 2.3.1, 2.4.2, Appendix A.8, Appendix B.3)

9. Collection of building energy, tree canopy area, human behavioral/psychological, and biodiversity data to assess more tree ES (building energy effects, human health benefits, habitat provisions and functions, etc.). Understanding how campus trees affect building energy expenditure, individual and community health, and ecological systems is a crucial next step in maximizing ES benefits and reducing campus carbon emissions. See Future Directions (Section 4) for more information. (Sections 1.5, 3.6, 4)

10. Recognition that campus forest carbon storage/sequestration is not a viable solution to University carbon emissions reduction. University Sustainability Plans should not rely on campus trees as a major source of carbon storage (0.459% University emissions) or sequestration (0.0088% University emissions) (Section 1.3.3), and FS cannot feasibly plant 1.28 million more hardwood trees to heighten this ES. Rather, other benefits that trees provide should be emphasized in sustainability planning. (Sections 1.3.1, 1.3.3, 2.3.1, 2.4.2, Appendix A.1, Appendix B.1)

1. Ecosystem Services

1.1 Introduction

Trees are an invaluable element of the University of Chicago's campus, providing numerous ecosystem services to the University and Hyde Park communities. Tree ecosystem services (ES) are defined as processes and functions of trees that directly or indirectly benefit human wellbeing (as opposed to general ecosystem processes and functions that have no relation to humans) (Costanza et al., 2017). ES is a framework through which the interdependence of humans and our surrounding natural environment can be quantified and better understood. More practically, focusing on the human benefits of trees will provide stronger justification for preserving the natural campus environment (e.g., when faced with construction projects). An understanding of tree ES along with careful tree planning and management will enable UChicago to maximize the benefits of its trees, improving the experiences of those who occupy campus and bringing the University closer to its sustainability goals.

We begin with a review of the main ES provided by urban trees: carbon storage and sequestration, air pollution mitigation, stormwater runoff management, urban microclimate regulation, building energy effects, noise attenuation, habitat provision and functions, human health benefits, aesthetic quality improvement, and oxygen production. Then, with insights from the 2020 UChicago i-Tree Ecosystem Analysis, we evaluate the relative significance of the ES provided by campus trees. We end with a discussion of potential tree ecosystem disservices, which should be taken into consideration when planning landscapes that minimize negative impacts on the UChicago and Hyde Park communities.

1.2 Ecosystem Services Overview

Many classification systems exist to group tree ecosystem services, but we have chosen to present ten prominent ES (as determined by a substantial literature review) without categorical grouping, because ES are multifaceted and do not often fit cleanly into one group. Furthermore, on our campus, particular ES or ES categories are not necessarily prioritized over others, so we present them with equal weight. Table 1 summarizes the ten selected ES and includes examples of their benefits. More thorough explanations of each ES are provided in Appendix A.

Ecosystem Service	Definition	Examples/Associated Benefits
Carbon storage/ sequestration	Total amount of carbon present in a tree, roughly equivalent to total biomass (storage) / rate at which reactant molecules of CO_2 are converted into biomass through photosynthesis (sequestration)	• Reduction of atmospheric carbon inventory

Air pollution mitigation	Removal of gaseous air pollutants through deposition to leaf surfaces and stomatal uptake	• Removal of NO_2, SO_2, O_3, CO, and PM10 • Improved air quality • Lowered rates of respiratory illness
Stormwater runoff management	Reduction of stormwater runoff volume due to root uptake/tree infiltration, canopy interception, and evapotranspiration	• Softened overflow burden on gray infrastructure (pipes and wastewater systems) • Reduction of soil erosion • Removal of water-soluble pollutants
Urban microclimate regulation	Amelioration of urban heat island effects (increased air and surface temperatures, solar radiation, humidity, and wind speeds) by provision of shade, evapotranspirative cooling, and wind flow intervention	• Improved pedestrian experience from more moderate temperatures and slower wind speeds
Building energy effects	Reduction of nearby building heating and cooling loads from shading, evapotranspiration, air pollution removal, and wind flow intervention	• Lower building energy costs • Decreased carbon emissions from buildings • Winter: lower heating load by blocking cold winds • Summer: lower cooling load by shading, evapotranspiration, and air pollution removal
Noise attenuation	Lowering of anthropogenic sound volume by tree sound reflection, refraction, scattering, and absorption, and addition of natural sounds to soundscape	• Increased perception of soundscape quality • Overall mood improvement from lowered noise level
Habitat provision and functions	Provision of shelter, shade, and foraging habitats to canopy- and ground-dwelling animals; increase of local soil nutrients and plant species richness; enhancement of biodiversity; bolstering of ecosystem resilience; other ecological functions that result from the presence of trees as keystone structures in urban ecosystems	• Increased animal presence (e.g., birds, arthropods) • Opportunities for outdoor education
Human health benefits	Numerous mental, physical, and community health benefits from looking at and interacting with trees	• Psychological relaxation, mood improvement, and attention restoration • Lowered rates of circulatory diseases and

		cardio-metabolic conditions • Higher general health perception • Heightened physical activity • Better student academic and behavioral outcomes • Lowered crime rates from increased casual surveillance
Aesthetic Quality Improvement	Beauty of trees and tree landscape design	• Calming and restorative effects • Environmental complexity and fascination to the human eye • Opportunities for exercise, recreation, and relaxation • Creation of a sense of place and identity
Oxygen production	Net amount of oxygen generated by tree processes of respiration and photosynthesis	• Increase of atmospheric oxygen inventory

Table 1: Ecosystem Services Overview

(Abdel-Aziz et al., 2015; Akbari & Taha, 1992; Asadian & Weiler, 2009; Astell-Burt & Feng, 2019; Berland et al., 2017; Berman et al., 2008; Bielinis et al., 2018; De Lacy & Shackleton, 2017; Escobedo et al., 2009; Fan et al., 2010; Grote et al., 2016; Hirokawa, 2011; Hosseinzadeh & Keshmiri, 2021; Kaplan, 1995; Kardan et al., 2015; Kuo and Sullivan, 2001; Manning et al., 2006; Matsuoka, 2010; McPherson, 2007; McPherson, 1998; Mitra, 2017; Nowak et al., 2018; Nowak et al. 2007; Pataki et al., 2011; Peters et al., 2011; Roy et al., 2014; Sakieh et al., 2017; Salmond et al., 2014; Sanusi et al., 2017; Schewenius et al., 2014; Shackleton & Blair, 2013; Shuster, Morrison, & Webb, 2008; Stagoll et al., 2012; Taha, 1997; Takano et al., 2002; Taylor & Kuo, 2009; Wang et al., 2019; Yasuda and Koike, 2009)

1.3 Ecosystem Services at UChicago

1.3.1 University Data: UChicago 2020 Tree Inventory and i-Tree Ecosystem Analysis Report Results

In 2020, the University of Chicago contracted Bartlett Tree Experts to conduct their third tree inventory and i-Tree campus forest analysis since 2010 with the aim of characterizing the campus forest and quantifying the value of campus trees. The inventory physically evaluated, measured, and labeled all 3764 campus trees, collecting data on species, height, diameter at breast height (DBH), canopy radius, planting type, risk assessment, location (using GIS software), and condition class (University of Chicago's *i-Tree Ecosystem Analysis*, 2020). The inventory provides useful data for campus budget development and succession planning. Further, these data were processed through i-

Tree's Eco software ("i-Tree Eco," 2019) and reported in the i-Tree Ecosystem Analysis to assess four ecosystem services: carbon sequestration and storage, air pollution mitigation, stormwater runoff management, and oxygen production. Building energy savings could be analyzed in the future as a potential fifth ES, but the proper data needed to conduct this evaluation were not measured in 2020.

To calculate the carbon storage ES, i-Tree uses species, DBH, total height, and land use, all essential for identifying and adjusting the correct biomass equation. For calculating carbon sequestration, i-Tree uses species, DBH, total height, and land use, but also includes model estimates of crown health and crown light exposure to adjust for growth rates. The i-Tree analysis estimates that campus trees store up to 1,204 tons of carbon, equivalent to a value of $205,000 or the annual emissions from 852 automobiles. The report estimates that UChicago's campus trees annually sequester 23.13 tons of carbon with an associated valuation of $3,950/yr or the annual emissions from 0 automobiles. Carbon valuation is based on "estimated or customized local carbon values." The report also found that honeylocusts (*Gleditsia triacanthos*) sequester and store carbon more than any other campus tree species at 24% of campus sequestration and 22.2% of campus storage. However, these large percentages of carbon storage and sequestration are due to the fact that honeylocusts (*Gleditsia triacanthos*) account for the largest number and percentage of trees on campus.

For the pollution mitigation ES, O_3, SO_2, and NO_2 are calculated based on hourly-tree canopy resistances derived from big-leaf and multilayer canopy deposition models. Since CO and PM2.5 are not related to transpiration like the previous pollutants, these values are instead calculated using averaged values from the literature, adjusted depending on a tree's leaf phenology and area. The i-Tree analysis estimates that University of Chicago campus trees remove up to 1,519 pounds of air pollutants like O_3, CO, NO_2, SO_2, and PM2.5 each year. According to the report, this air pollution mitigation equates to $21,400/yr, as calculated based on the "incidence of adverse health effects" and the U.S. median externality costs for each pollutant (i.e., "the estimated cost of pollution to society that is not accounted for in the market price of the goods or services that produced the pollution" (Nowak, 2020)).

To calculate the avoided stormwater runoff ES, the i-Tree analysis evaluates both shrubs and trees and bases its precipitation data on a nearby weather station. i-Tree uses percent tree cover and leaf area index, which are estimated from a tree's species, total height, crown base height, crown width, and crown missing percent. The report states that UChicago received 36.7 inches of total precipitation in 2016 (the most recent weather data used in i-Tree) and estimates that campus trees and shrubs help reduce stormwater runoff by approximately 49.7 thousand cubic feet per year. This amount has an associated valuation of $3,320/yr, as calculated using "estimated or user-defined local values."

For the ES of oxygen production, the report calculates values based on atomic weight and net carbon sequestration. i-Tree estimates that University of Chicago campus trees roughly produce 61.68 tons of oxygen per year, with the honeylocust species (*Gleditsia triacanthos*) being the top oxygen producer due to its substantial numerical presence on campus.

1.3.2 Most Impactful ES

While the University of Chicago's campus trees provide many ecosystem services, not all are equally effective in advancing the University's sustainability goals (The University of Chicago Office of Sustainability, 2016), fostering ecological communities, and improving human health and satisfaction. In particular, several of the ES have greater effects on the campus community: urban microclimate regulation, air pollution mitigation, building energy effects, habitat provision and functions, human health benefits, and aesthetic quality improvement. The remaining four ES, carbon storage/sequestration, stormwater runoff management, noise attenuation, and oxygen production, are less impactful on campus due to their scale; larger forests are required for these ES to be highly impactful. Impactfulness is determined by i-Tree quantification, as well as an extensive literature review of the small- and large-scale impacts of ES. As discussed later in Section 1.5: Areas for Future Investigation, many of these ES are not totally quantifiable, and not all required data for quantification have been collected specifically at UChicago. However, these six ES contribute considerably to the campus and Hyde Park communities, and we recommend that they be taken into planning considerations as the University continues to strive for a sustainable campus. These six ES are presented below in no particular order. Urban microclimate regulation and air pollution mitigation are combined due to their related benefits on campus.

Urban microclimate Regulation and Air Pollution Mitigation

Located in the third most populous city in the U.S., UChicago is not exempt from the urban heat island effect or the air quality detriments of urban pollution. The microclimate produced by campus trees through shading and evapotranspiration, and the air pollution mitigation trees provide through leaf deposition and stomatal uptake, have the potential to significantly improve campus and neighborhood temperature, humidity, and air quality. Additionally, trees can help regulate uncomfortable wind speeds when planted strategically. For example, large trees in places with high-velocity winds (such as areas around campus buildings that experience wind tunnel effects) could help slow wind speeds, reduce the downwashing and corner wind effects, and improve the pedestrian environment. Urban microclimate regulation and air pollution mitigation are thus two of the most impactful ES at UChicago due to their ability to change local temperatures and air quality, and effort should be put into better quantifying and enhancing these services.

Building Energy Effects

The building energy effects of campus trees are lacking in data (building coordinates, tree distances from buildings, heights of buildings, wind speeds, and annual building energy use), though this ES has a large potential impact on University greenhouse gas emissions. Since tree carbon sequestration and storage offsets little carbon emissions, as discussed below in Section 1.3.3: Least Impactful ES, reducing the amount of energy used for building temperature regulation could offer an alternative way to cut down University carbon emissions. Chicago's climate includes both extreme hot and cold periods, as well as fast winds, making it harder to regulate inside temperatures than in a more temperate or less weather-variable location. Tree shading could be used to effectively lower building cooling loads in the summer, whereas tree placement around buildings could block icy winds in the winter and reduce uncomfortable wind speeds year-round. Building energy effects is a significant University tree ES for its palpable effects on decreasing campus energy expenditure.

Habitat Provision and Functions

Greenspace, though crucial for a number of ecological, economic, social, and personal reasons, is often limited in cities. As a result, planting even one additional tree in an urban environment can have a much greater impact than planting one in a forest (Manning et al., 2006). The UChicago campus is home to a wide variety of ecologically connected flora and fauna, so removing keystone structures like trees due to construction could have a major negative impact on the local ecosystem. Conversely, planting a single tree can have a positive effect on local biodiversity by increasing habitat area, soil nutrients, and ecological connectivity. As discussed in Section A.7: Habitat Provisions and Functions, increasing biodiversity makes ecosystems more resilient and sustainable, in turn benefitting human health and favoring climate change adaptation. Habitat provisioning is thus a crucial ES in sustaining the campus' ecological network and encouraging long-term campus forest health.

Human Health Benefits

The University of Chicago is widely recognized as one of the nation's top universities due to its academic rigor. Unfortunately, this environment can place immense stress on students. Additionally, though there have been conflicting results, many studies report that living in a metropolitan area can contribute to lowered mental health, evidenced by Peen et al.'s report (2010) stating that cities have higher rates of mood and anxiety disorders. Given this combination of negative health factors, the mental and physical health benefits provided by UChicago trees are incredibly valuable: students burdened by intense course loads and personal struggles can walk through campus or look out building windows to receive psychological benefits from trees. An additional consideration is that many students are busy and may not have time to participate in traditional de-stressing activities (e.g., yoga, meditation, prayer), so the necessary commute to class can help to relieve stress (due to the presence of trees and other greenery) without adding an extra time commitment. The contribution of trees to UChicago community health is also valuable in regard to crime. The violent crime rate in the Hyde Park-South Kenwood community, though lower than the Chicago citywide average, was appreciable at 487 incidences per 100,000 people in 2020 ("Crime Trends," 2021). Given that the presence of trees may increase informal surveillance by encouraging greater use of outdoor areas, it is worth investigating this correlation on the UChicago campus. Better understanding of trees' effect on crime can aid University safety infrastructure (e.g., by planting trees in more deserted areas) and add to the growing body of research on nature and social deviance.

Aesthetic Quality Improvement

UChicago's campus features beautiful collegiate gothic architecture and verdant grounds, of which trees are a primary aspect; their contribution to the University's visual aesthetic should not be undervalued. The campus became certified as a botanic garden in 1997 ("Botanic Garden Initiative," 2021) and is currently in the process of becoming a certified Tree Campus USA. The beauty of trees can help students take pride in their campus and school, enhancing the UChicago community network and potentially aiding in alumni retention. The beautification that trees add to campus also makes outdoor spaces appealing places to cultivate learning and encourages students and faculty to be outside for recreational purposes as well.

1.3.3 Least Impactful ES

Carbon storage/sequestration, stormwater runoff, and oxygen production, despite quantification within the 2020 i-Tree Ecosystem Analysis, are three ecosystem services that do not provide relatively many benefits to the campus and Hyde Park communities. Noise attenuation, while not included in the i-Tree Ecosystem Analysis, is also less impactful due to the environment of the University. These four ES are presented below in no particular order.

Carbon Storage/Sequestration

According to i-Tree, UChicago 2020 carbon storage and sequestration were valued at $205,000 for 1,204 tons of carbon and $3,950/yr for 23.13 tons of carbon, respectively. Taking a yearly University carbon emissions value of 25.2 kg eCO_2/sq ft (The University of Chicago Office of Sustainability, 2016) and a campus land area of 217 acres ("About the University," 2021), the University emits about 238,215,600 kg (262,588 tons) of CO_2 each year. Thus, we estimate that campus trees store only 0.459% and sequester only 0.0088% of campus carbon emissions; the carbon storage/sequestration ES is insignificant due to its scale. Though this carbon calculation is only a rough estimate due to the use of data from multiple sources and years, it provides a useful metric for understanding the comparatively small amount of campus carbon uptake as opposed to campus carbon emissions. It must also be noted that each tree stores and sequesters a different amount of carbon based on its size and species, so these values are quite general. To raise campus tree carbon sequestration to 10% of total annual campus carbon emissions (25.2 kg eCO_2/sq ft), the campus forest would need to sequester 26,284 tons of carbon. According to the U.S. Department of Energy: Energy Information Administration (1998), a 20-year-old hardwood tree sequesters 41 pounds of carbon per year. Hence, the University would need to plant and maintain 1,281,022 more hardwood trees (over 340x the current number of trees) to sequester 10% of the carbon the University emits each year. We thus conclude that carbon storage/sequestration, compared to the scale of the University as a carbon source, is not an impactful ES provided by the campus forest.

Stormwater Management

Stormwater management is another ES quantified in the 2020 i-Tree Ecosystem Analysis. According to i-Tree, campus trees prevent 49,740 cubic feet of annual runoff, valued at $3,320/yr. UChicago's 2016 Sustainability Plan reports that the campus receives over 194 million gallons of rain each year. With appropriate conversions, campus trees offset only 0.192% of annual stormwater. Much campus area is covered by impervious land and non-tree green space, so total stormwater management by trees is not a feasible goal. To raise campus tree stormwater runoff prevention to 10% of annual received rainfall (194 million gallons), the campus forest would need to offset about 2,593,403 cubic feet of runoff. Peter MacDonagh, the Director of Design and Science at Kestrel Design Group (Minneapolis), reports that a 20-year-old tree intercepts about 1350 gallons, or 180.5 cubic feet of stormwater per year (Fulcher, 2012). Hence, the University would need to plant and maintain about 14,368 more trees (3.82x the current number of trees) to manage 10% of University stormwater runoff. Younger trees offset lower amounts of stormwater while older trees offset higher amounts, so the University would need to plant even more trees to offset stormwater imminently (before the trees age). Due to the small percentage of current tree stormwater management, we determine that it is not a relatively significant ES on UChicago's campus.

Oxygen Production

A third less-significant ES provided by campus trees is oxygen production, also quantified in the 2020 i-Tree Ecosystem Analysis. i-Tree states that UChicago's trees produce 61.68 tons of oxygen per year, adding a minute amount to the 1.2 quadrillion metric tons of O_2 already in the atmosphere (Keeling, 2013). Since burning all fossil fuels, soil organic matter, and trees would only decrease the atmospheric oxygen concentration by a few percent (Broecker, 1970, as cited in the University of

Chicago's *i-Tree Ecosystem Analysis*, 2020), we surmise that oxygen production is not one of UChicago's crucial tree ES.

Noise Attenuation

Lastly, though not quantified by i-Tree, we propose that noise attenuation is not a significant ES provided by the University's campus trees. While noise attenuation is a valuable service in busy urban areas, Hyde Park is significantly quieter than many Chicago neighborhoods, especially those nearer to the Loop. Hyde Park is home to about 27,500 residents (Chicago Metropolitan Agency for Planning, 2021), ranking 45th in population among Chicago's 74 neighborhoods (City of Chicago, 2010). While Hyde Park's population density is about 15,221 people/sq mi, 3,251 people/sq mi more than Chicago's population density (Hyde Park Chamber of Commerce, 2016), there is generally a low amount of vehicular and railway transportation on and surrounding campus (except for the Midway, as studied by UChicago Professor Mark Berman). In fact, the University explicitly discourages vehicular traffic on campus, even offering housing stipends to professors who live close to campus (UChicago Sustainability Plan, 2015). While construction is ongoing on campus, it is more prominent during the summer months when fewer residents inhabit campus and nearby apartment buildings. Thus, while noise attenuation is an impactful ES in urban environments, it does not have a large impact on the University of Chicago campus.

1.4 Ecosystem Disservices Overview

Urban trees provide many ecosystem services and benefits, as discussed extensively in this report. However, urban trees also provide processes and functions that negatively impact humans, called tree ecosystem disservices (EDS) (Costanza et al., 2017). EDS either harm the environment or bring overall displeasure to humans (Lyytimaki & Sipila, 2009). Tree EDS are crucial to understand and quantify so ecologists, economists, and urban planners can fully justify trees' significance in an urban environment. A bias towards ES could lead to potential oversights when implementing plans for the future of an urban forest (Delshammar et al., 2015). As a solution, officials should recognize that while most disservices are inevitable, they are also manageable; this argument should be included when making an argument to increase the campus forest. Ostberg et al. (2015) demonstrate how landscapers and urban planners can avoid or minimize disservices by explaining that, for example, if complaints arose about vegetation interfering with infrastructures, then trees with smaller sizes could be selected to accommodate for the limited spacing. If a tree produces nuisance fruits or seed pods, on the other hand, sterile hybrids might be more appropriate.

Most ecosystem disservices are categorized as either environmental hazards, health and safety hazards, economic hazards, or visual and aesthetic hazards, and examples are given in Table 2. Low-income or minority community members that reside in underprivileged areas may negatively view their community trees because they symbolize adversity from systematic redlining and historical failures by the government in managing environmental issues (Carmichael & McDonough, 2019). Residents of these neighborhoods often decline free street trees near their homes for fear of taking on maintenance responsibilities and from frustration at a lack of autonomy in the species selection and planning processes (Mock, 2019). Environmental justice may be closely tied with an EDS framework; negative perceptions of trees may be ameliorated by proven governmental accountability and genuine community education and involvement.

Some of the most prevalent environmental hazards of trees include: release of biogenic volatile organic compounds (BVOCs), displacement of native species, introduction of invasive species, energy consumption and pollution from maintenance, and carbon and methane emissions from decomposition. BVOCs are an important EDS to consider because as plants emit them, a variable increase in PM2.5 concentrations and ozone pollution at ground-level results, leading to detriments to air quality and human health (Ren et al., 2017). BVOC emission patterns are difficult to trace, however, because the species of a tree and the urban heat island effect drastically change their estimated values; indeed, environmental researcher Jonathan Abbatt states that VOC sources are difficult to differentiate (Naranjo, 2011). As worldwide urbanization continues, VOC emissions will become increasingly dangerous to human health. While VOC emissions and related health complications are pressing issues, especially in cities, trees should not be deemed fully responsible, in part due to their numerous air pollution alleviation benefits. Additionally, lower BVOC-emitting tree species can be selected (e.g., sugar maple (*Acer saccharum*), hackberry (*Celtis occidentalis*), littleleaf linden (*Tilia cordata*), London planetree (*Platanus x acerifolia*) (Curtis et al., 2014)), since some species emit about 100,000x more BVOCs than others (Simpson & McPherson, 2011). For more information on low-BVOC emitting tree species, see Table 7 in Appendix C.

With the exception of these noted environmental hazards, EDS mainly stem from personal preferences (e.g., leaves falling on a lawn) or singular accidents (e.g., tree branch falling on a car). EDS are mostly quantifiable through field surveys and questionnaires, which contributes to why disservices research has been limited until recent years. Further research is needed to fully establish the relationships between all existing ecosystem disservices and their services counterparts (Lyytimaki, 2017).

Environmental Hazards	• Propagation of invasive species • Displacement of natural species by invasive or non-native species • Methane emissions from decomposition • Energy and resource consumption through planting and maintenance • Pollution and carbon released from maintenance
Health and Safety Hazards	• Emission of biogenic volatile organic compounds (BVOCs) • Slippages caused by fallen leaves and fruits • Injuries and insurance liabilities caused by fallen branches • Pollen-related allergies • Insect bites/attacks from hosted species • Toxic or poisonous substances • Diseases transmitted by hosted species • Fear of crime hidden by tree-provided darkness
Economic Hazards	• Maintenance costs: pruning, planting, replacement, green waste removal, transplants • Pest control and disease treatment costs • Unwanted species removal costs

Aesthetics and Visual Hazards	• Undesirable look if not properly maintained • Tree-hosted species that provide aesthetic discomfort • Obscured views • Darkness • Damage to infrastructure and buildings

Table 2: Ecosystem Disservices Examples

(Cariañanos et at., 2017; Delshammar et al., 2015; Escobedo et al., 2011; Lyytimaki, 2017; Vaz et al., 2017)

1.5 Areas for Future Investigation

The 2020 University of Chicago i-Tree Ecosystem Analysis, while valuable, only provides data on four of the ten previously discussed ecosystem services listed in Table 1: carbon storage/sequestration, pollution mitigation, stormwater management, and oxygen production. These ES are quantified using equations and models, while others are more nuanced and require qualitative data like interviews and surveys. To quantify additional ES, data on more variables need to be collected in future surveys by Bartlett. Alternatively, students or Facilities Services could collect these data on a subset of trees.

One area of potential further quantitative research for the UChicago campus is building energy effects. The building energy ES encompasses reduction of carbon emissions from campus buildings, which is a principal consideration in the University's sustainability goal of 50% greenhouse gas reduction by 2030 (The University of Chicago Office of Sustainability, 2016). Bartlett and UChicago did not collect the necessary data to calculate tree contributions to building energy savings and carbon reduction, though the i-Tree software can quantify this service. In future Bartlett inventories or other University data efforts, we strongly recommend collection of building coordinates, tree distances from buildings, heights of buildings, wind speeds, and annual building energy use to determine more quantifiable sustainable and fiscal impacts of campus trees. Urban microclimate regulation and noise attenuation are other quantifiable ecosystem services, though they are not currently within i-Tree software's capabilities. Trees' effects on microclimates can be modeled with equations from the literature, while the noise reduction abilities of individual tree species have been experimentally determined and can be applied to the campus forest through simple multiplication (e.g., maple tree noise reduction constant * number of maple trees on campus = total noise reduction by maple trees on campus). Assessing and quantifying the impact of trees on campus and Chicago microclimates can further the body of research on the benefits of nature in urban environments. While noise attenuation is an often-overlooked ecosystem service, it continually benefits the campus soundscape and should be quantified for a better understanding of the functional value of UChicago's trees.

Gaining a full picture of the unquantified ES provided by UChicago's campus also requires collection of qualitative data like natural observations, student/faculty surveys, and community interviews. For one, habitat provision can be assessed through visual observation of the animal species that inhabit or visit campus trees, combined with measurements of tree size and species to determine associations between certain trees and their biodiverse communities. Student, faculty, and community volunteers could aid in reporting animals seen on or around campus trees and collecting data on pollinator visitation, nesting birds, bird point counts, fruit/seed consumption by particular animal species, and other ecological observations. For trees' effects on physical and mental health, student, faculty, and community interviews, surveys, and focus groups can be used to gauge personal assessment of tree benefits on mood and stress. Some quantitative techniques of assessing mental health have been developed based on the correlation of various health improvements with different levels of exposure to nature (e.g., calculating what percent of a window view is occupied by green space). Conducting research in many campus locations, such as the medical campus, classroom buildings, dormitories, and quadrangles will contribute to a better understanding of how UChicago's trees serve community health. Lastly, aesthetics can be assessed through interviews, surveys, and focus groups conducted with a representative group of campus-goers (i.e., students, faculty, staff, community members).

More research and quantification are needed in the University of Chicago's mission to evaluate and advocate for its campus forest. Once more data are collected, the six ecosystem services not covered by the 2020 i-Tree Ecosystem Analysis (building energy effects, urban microclimate regulation, noise attenuation, habitat provision and functions, human health benefits, and aesthetic quality improvement) can be assessed using existing equations, models, and qualitative techniques to further analyze and promote UChicago's urban trees and Hyde Park's biodiverse community.

1.6 Conclusion

The University of Chicago's urban forest provides a number of benefits to the campus and Hyde Park residential and ecological communities. Ecosystem services is just one useful framework for assessing such benefits, and its accompanying ecosystem disservices framework helps ground efforts to support and grow the campus forest. While numeration and valuation of each ES has not yet been conducted, general assessments of these services can be performed to illustrate the many environmental, economic, and health benefits of campus trees. Studying and reporting the ES of campus trees is also useful for justifying the monetary value of each tree. Trees provide much more than their structural value (e.g., cost of replacing a tree with a similar tree), which i-Tree denotes as a tree's functional value (e.g., functions or services trees provide) (University of Chicago's *i-Tree Ecosystem Analysis*, 2020). Functional value is highly representative of an ecosystem services framework and can be critical when pricing a tree (for example, when considering its removal for construction projects). Well-rounded assessments of individual tree valuations and provisions is crucial in upholding UChicago's urban forest and its associated benefits. Due to the variety of goods and services provided by campus trees, we encourage proper maintenance and thorough care of the University's urban trees and soils. We also recommend more in-depth quantification of our own campus tree ES to assess the true total value of the UChicago campus forest. Adopting an ES framework, often in conjunction with other analytical frameworks, increases awareness of the benefits of trees and furthers an agenda of appreciating and prioritizing green space in urban settings. Hence, trees are a key element of advancing the sustainability of UChicago's campus, aiding in the mitigation of global climate change and improving local conditions for the benefit of all.

2. Climate Change

2.1 Introduction

Climate change is a growing, imminent threat raising interdisciplinary concern. Climate change impacts ecology, biodiversity, economics, human health, and environmental health, among other fields. Trees exist at the intersection of many of the changing climate's global effects. As living organisms adapted to specific habitat and temperature conditions, climate change may cause certain tree species to become ill-suited to the regions they currently inhabit. The potential resulting tree loss and range shifts will negatively and differentially impact the ability of trees to provide the valuable environmental, economic, health-improving, and otherwise beneficial ecosystem services (ES) detailed in Section 1: Ecosystem Services. Understanding the projected effects on campus tree ES allows for succession planning that continually upholds ES by choosing trees predicted to withstand an altered climate. Trees will indeed exhibit "adaptive capacity" based on many species-specific factors, meaning that a variety of traits that characterize a species will make it more or less able to persist in predicted future conditions. Proper planning and maintenance of the University of Chicago's urban forest, including maximization of campus tree ES, requires an understanding and incorporation of how climate change may affect campus trees.

We begin with a discussion of the past, present, and future Chicago regional climate, and then an overview of how climate change is predicted to impact trees, including possible effects on tree ES, USDA hardiness zones, and pests/diseases. Next, we discuss consolidated survival expectations for tree species found on campus and identify potential adaptation actions. Finally, we explore how UChicago tree ES may be affected by climate change and detail methods by which the university could evaluate changes in its trees' performance.

2.2 Past, Present, and Projected Trends in Chicago Climate

2.2.1 Past and Present Changes

The Earth's climate has undergone vast changes since at least the mid-1850s as human fossil fuel burning and dramatic land-use changes added large quantities of greenhouse gasses to the atmosphere. These climate changes have varied greatly by region, forcing different parts of the world to face unique obstacles and find distinct solutions to work towards sustainable development. Moreover, climate change amplifies existing challenges to urban areas stressed by large populations and aging infrastructure. Within cities, the effects of climate change are not equally felt, as low-income and minority populations are often disproportionately affected by poor air quality, environmental hazards, inadequate infrastructure, and slower recovery after natural disasters (Patnaik et al., 2020). Such communities often have lower access to resources such as green space and economic means that could help increase their resilience to climate effects (Sharma et al., 2018). In Chicago, some of the most notable impacts of climate change have been increased temperature and precipitation, according to a recent Illinois climate assessment (Wuebbles et al., 2021). Over the last 120 years, the average daily temperature in Chicago has risen by 1-2°F while the overnight minimum temperature has risen by close to 3°F. Annual total precipitation has increased by 10-20%; the number of days with extreme precipitation (2 or more inches) has gone from an average of fewer than 1.5 (from 1900-04) to over 2.5 (from 2015-18). Increased precipitation, along with land development patterns, has driven flooding, while extreme droughts have become less common. However, since higher temperatures have caused greater soil evaporation and annual evapotranspiration has increased, crops and ecosystems have been placed under compounding water stress during dry summer months. The risk of short-term drought is increasing in Chicago and the Midwest. Both rapidly changing temperatures and precipitation are stressing Chicago's natural habitats and creating conditions more conducive to weeds, pests and diseases.

2.2.2 Projected Trends

The University of Chicago and its trees will continue to face numerous challenges as the effects of climate change escalate over the course of the 21st century. Table 3 summarizes current conditions and projected climate changes for northern Illinois between the recent historical period of 1990-2019 and the century-ending period of 2070-2099, sourced from Wuebbles et al.'s 2021 report. The researchers make future climate predictions for the Chicago area based on both a low emissions scenario (assumes a swift movement away from the use of fossil fuels) and a high emissions scenario (projects a continuing rise in carbon and methane emissions). Under the high emissions scenario, the predicted weather changes are more severe, but weather in Chicago is likely to become more extreme regardless of which scenario is realized.

Dramatic warming is expected for the Chicago region, with temperature increases across all seasons (Brandt et al., 2017a). Wuebbles et al. (2021) find that, by the end of the century, the annual average temperature could be as high as 63°F, up from the current 49°F. Precipitation is also projected to increase significantly (up to 20% annually), but the expected changes differ significantly by season, with large increases in winter and spring and a moderate decrease in summer. Heavy rains and the length of dry spells are both expected to increase, as is the intensity of maximum heat. The annual hottest 5-day maximum temperature could reach as high as 110°F under the high emissions scenario, and the number of days with a maximum temperature of at least 100°F could reach 65 (it is currently less than 1). The frequency of warm nights will likely increase as well. Conversely, the number of extreme cold days is expected to decrease, as is the length of the freeze-free season (i.e., the time between the last spring and first fall occurrences of 32°F). The annual coldest 5-day minimum temperature, currently -6ºF, is projected to rise as high as 17°F. The number of days with freezing nighttime temperatures (minimum of 32°F or lower) is also expected to decrease notably.

Rising temperatures mean that the atmosphere will be able to hold a greater amount of moisture, which will also contribute to extreme weather by increasing the frequency and intensity of heavy rain and snow (Wuebbles et al., 2021). Additionally, as Arctic temperatures warm faster than the rest of the planet, the polar jet stream that restrains the extreme cold of the polar vortex (which is itself weakening and fragmenting due to warming) is distorting. This distortion allows warm southerly air to more easily reach the Arctic, which then allows the polar vortex to stretch into the U.S. Midwest (Chicago Tribune Staff, 2019). The potential for unpredictable episodes of intense cold mixed into a general warming trend throughout the century could prevent many tree species from thriving in the Chicago region (Brandt et al., 2017a).

	Present data	Future projections			
	1990-2019	2070–2099 low emissions	**Low emissions difference**	2070–2099 high emissions	**High emissions difference**
Annual average temperature (°F)	49	52-58	**+3-9°F**	57-63	**+8-14°F**
Annual hottest 5-day maximum temperature (°F)	92	96-104	**+4-12°F**	100-110	**+8-18°F**
Days with maximum temperature ≥ 95°F	<5	15-60	**+10-55 days**	25-90	**+20-85 days**
Days with maximum temperature ≥ 100°F	<1	1-25	**+0-24 days**	5-65	**+4-64 days**
Nights with minimum temperature ≥ 70°F	10	20-60	**+10-50 days**	45-95	**+35-85 days**
Nights with minimum temperature ≥ 80°F	~0	0-3	**+0-3 days**	2-25	**+2-25 days**
Annual coldest 5-day minimum temperature (°F)	-6	0-10	**+6-16°F**	7-17	**+13-23°F**
Days with minimum temperature ≤ 32°F	135	95-120	**- 15-40 days**	60-100	**- 35-75 days**
Length of freeze-free season (days)	160	170-200	**+10-40 days**	190-220	**+30-60 days**
Annual total precipitation (in)	35	34-40	**- 0-1in +0-5in**	34-42	**- 0-1in +0-7in**
Winter total precipitation (in)	6	7-8	**+1-2**	7-9	**+1-3**
Spring total precipitation (in)	11	11-14	**+0-3**	12-14	**+1-3**

Summer total precipitation (in)	11	9-13	**- 0-2 +0-2**	8-13	**- 0-3 +0-2**
Days with precipitation ≥ 2in	0.4	0.3-0.6	**- 0.1 days +0-0.2 days**	0.4-0.9	**+0-0.5 days**
Annual maximum number of consecutive dry days	12-14	13-16	**+1-2 days**	13-17	**+1-3 days**

Table 3: Projected Climate Changes for Northern Illinois. *The table contains late 21st century climate projections based on low (yellow) and high (red) emissions scenarios. Low emissions scenario is RCP4.5, in which there is a rapid movement away from fossil fuels in the next few decades. High emissions scenario is RCP8.5, in which carbon and methane emissions continue to rise over the course of the century. Differences between late century projections and present observations for each climate metric are bolded and provided in columns 4 (low emissions scenario) and 6 (high emissions scenario).*

(Wuebbles et al., 2021)

The water-related impacts of climate change predicted to hit Chicago are particularly salient, as the city may not only experience greater precipitation and changing drought patterns but is positioned next to lake Michigan, intersected by the Chicago and Calumet rivers, and home to stormwater and sewage systems that serve around five million people (MWRD, 2016). Over the next century, more severe droughts and heat waves are projected to accompany hotter summers as well as increase in length, frequency, and spatial extent (Brandt et al., 2017a). Yet, more intense precipitation (particularly in the spring) will likely increase runoff and cause flooding to become more common, placing additional stress on Chicago's water management systems which are already prone to flooding and leakage (Natural Resources Defense Council, 2011). Rather than cancelling out, the predicted patterns of increased temperature and precipitation are expected to each present distinct, escalating challenges. Weeds, pests, and diseases will likely intensify due to higher temperatures in addition to increased precipitation (The Nature Conservancy, 2021). Also, an eastward trend of tornadoes in the U.S. is set to increase the frequency of tornadoes in Chicago (Chicago Tribune Staff, 2019), which could uproot trees. Climate change will continue to present mounting challenges to Chicago and the world. It is therefore imperative for UChicago to plan for urban forest adaptation and resilience.

2.3 Trees and a Changing Climate

2.3.1 Ecosystem Services Provision

Increasing global temperatures, extreme weather events (e.g., forest fires, hurricanes, droughts, floods, landslides) and new pests and pathogens threaten individual trees and urban forests. As trees are faced with reduced habitat area and rapidly changing conditions, their ability to provide ecosystem services will decline. Breshears et al. (2011) predict that climate change will result in "extensive losses of ES" due to big, fast, patchy ecosystem crashes, which Nelson et al. (2013)

corroborate. Bugmann et al. (2014), however, propose that ES climate change vulnerability will vary considerably by service. Persistence of ES is also highly dependent on carbon emissions scenarios (low vs. high) and on the species of tree (Brune, 2016; Meineke et al., 2016; Ordóñez & Duinker, 2014; Rötzer et al., 2019; Van Houtven et al., 2019).

Generally, researchers predict warming and increased nitrogen deposition to favor tree biomass growth in the next few decades, in turn favoring increased ES provision (Locosselli et al., 2019; Meineke et al., 2016; Pretzsch et al., 2017). Increased tree growth rates lead to earlier provision of many ES, but also favors rapid aging and fast tree replacement, which can be costly in both money and carbon emissions. Models project that future drought stress and extreme weather patterns will cause tree dieback and mortality around 2040-2070, leading to an overall decrease in ES provision (Breshears et al., 2011; Pretzsch et al., 2017; Solomon & Kirilenko, 1997; Zaehle et al., 2007). Lowered nutrient availability from urban soils and future lessened biomass growth will also exacerbate tree stress and therefore limit ES provision (Breshears et al., 2011; Rötzer et al., 2018; Zaehle et al., 2017). High urban air pollution levels can cause additional decrease in ES from tree stress (Pouyat et al., 1995, as reported in Schwendenmann & Mitchell, 2014). Some ES, like habitat provisions and functions, human health benefits, and aesthetic quality improvements are not predicted to decrease with climate change. While many trees may suffer from stress and mortality, these three ES are favored by the presence of any trees; by contrast, ES like carbon storage and sequestration and stormwater runoff management are only impactful when a large amount of trees are present, meaning they have the potential to decrease significantly with climate change. For more detailed information on climate change and ES provision, see Appendix B.

2.3.2 USDA Plant Hardiness Zones

In 2012, the United States Department of Agriculture (USDA) released an updated, GIS-based Plant Hardiness Zones Map (PHZM) developed by USDA Agricultural Research Services (ARS) and the Oregon State University PRISM Climate Group (USDA, 2012) and shown in Figure 2. PHZMs represent the average annual minimum temperature of specified regions. The 2012 iteration uses data from the 30-year period of 1976-2005 (USDA, 2012). The updated map has 13 temperature zones that each span 10ºF, with subzones of 5ºF denoted “a” and “b” (USDA, 2012). Zone 1a has average minimum temperatures of around -60ºF, while Zone 13b has average minimum temperatures of around 65ºF (USDA, 2012).

Plant Hardiness Zones (PHZ) are relevant to planting considerations because they account for the differing amounts of temperature stress species can withstand (USDA, 2012). “Cold hardiness” denotes the coldest minimum temperature that a fully dormant plant can survive and it is highly species-specific (USDA, 2012). Damage or mortality from low temperatures can occur during the autumn, midwinter, or late winter/early spring based on plant growth and physiology (Daly et al., 2012). Injury can also occur during atypical, mild freeze events when growing plants are temperature shocked (Daly et al., 2012). Plants can become severely damaged due to common stressors that work in conjunction with temperature variability (e.g., extreme high temperature events, high nighttime temperatures, moisture-balance disruptions, discontinuity of cloud and snow cover) (Daly et al., 2012).

PHZ are predicted to shift as annual rises in winter temperatures accompany global warming trends. Interestingly, the coldest annual minimum temperatures are predicted to rise more than the average annual minimum temperatures, making the PHZM an accurate model over reasonable timespans. Since the 1990 PHZM, on average, each half-zone has warmed by 5ºF. USDA Public Affairs Specialist Kim Kaplan notes that the longer time period of data collection, as well as data collection from more stations, largely explain the consistent temperature rises (2012). Additional factors like elevation, proximity to large bodies of water, and terrain positioning were also newly taken into account on the 2012 PHZM, enabling more accurate zonation than previous iterations (Kaplan, 2012).

The Yale School of the Environment reports that PHZ are moving northward at a rate of 13.3 miles per decade, leading to palpable shifts in survivable plant species ranges. Range expansion is not always a bad thing, however. Species ranges have changed over time for millions of years without human assistance and often expand the area of habitat provisioning. As for Illinois, the Illinois State Climatologist reports that the Zone 5/6 boundary (-10 to -20ºF/0 to -10ºF) shifted about 60 miles northward between the 1990 and 2012 PHZM, while Zone 4 (-20 to -30ºF) fully left the state (see Figure 1 for a map of current PHZ). In addition to zonal changes, annual temperature variability on smaller scales is significant (Angel, 2012). Chicago specifically falls within Zones 5b/6a (-10 to -15ºF/-5 to -10ºF) due in part to the urban heat island effect. Furthermore, some effort has been made to predict future PHZ shifts. Brandt et al. (2017b) predicted zonal shifts in Chicago for 30-year periods up to 2099 under low and high greenhouse gas emissions scenarios (results presented in Table 4). The researchers' results identify the connection between climate modelling and actionable forestry and city management; the University of Chicago and other university and urban forests should make tree selections with current and future PHZ in mind.

	1980-2009	2010-2039	2040-2069	2070-2099
Hardiness Zone (Low Emissions)	5b-6a	5b-6a	6a-6b	6a-6b
Hardiness Zone (High Emissions)	5b-6a	6a-6b	6b-7a	7a-7b

Table 4: "Current and projected USDA Hardiness Zones in Chicago under low and high greenhouse gas emissions scenarios" *(Brandt et al., 2017b)*

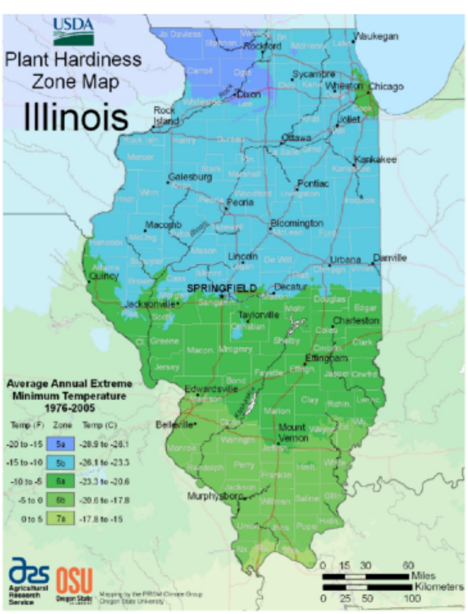

Figure 1: USDA Plant Hardiness Zone Map Illinois

(USDA, 2012 as cited by Angel, 2012)

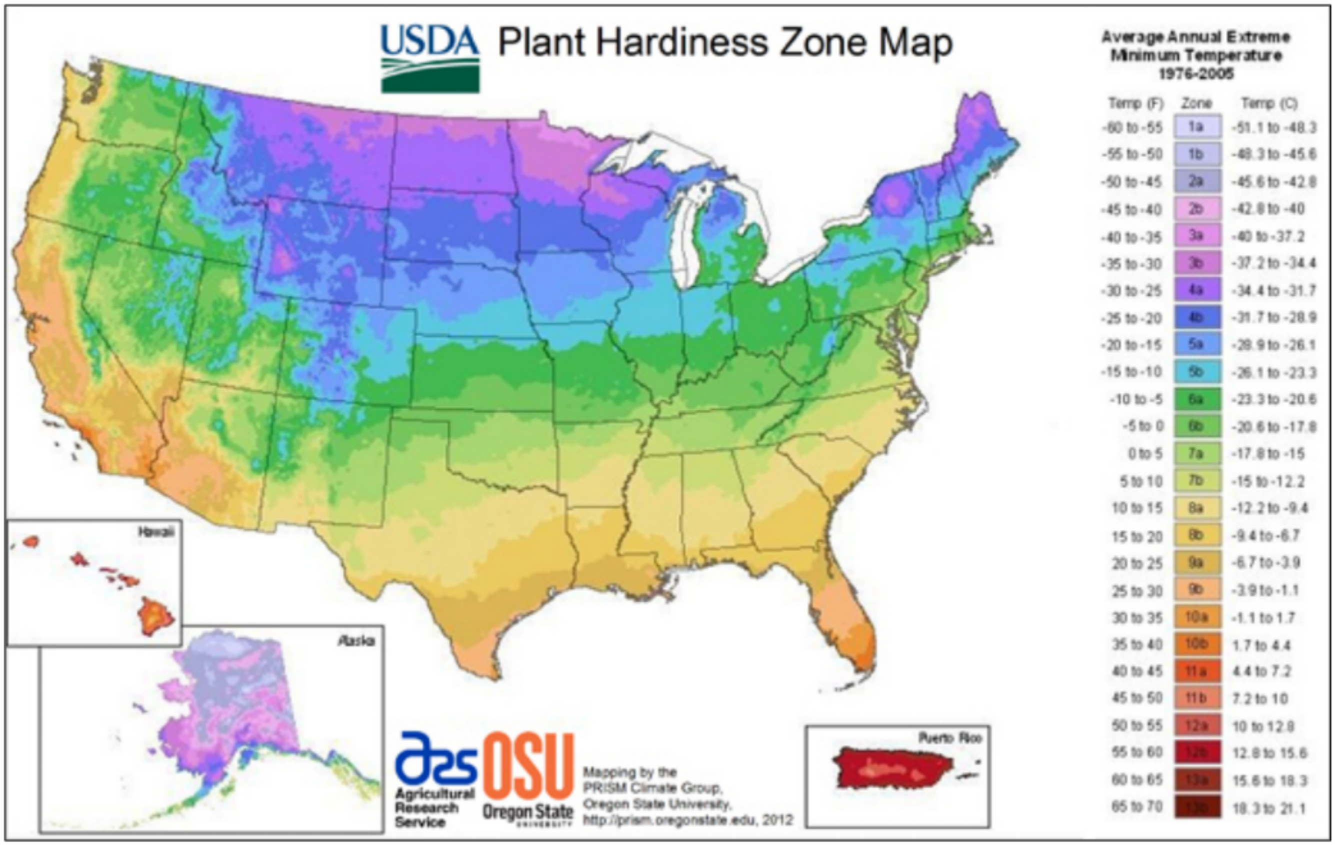

Figure 2: USDA Plant Hardiness Zone Map

(USDA, 2012)

2.3.3 Pests and Disease

Human activities that contribute to climate change increasingly challenge the health of urban forests, rendering trees susceptible to infection from pests and pathogens. Pests and pathogens cause significant damage, destruction, and disease to healthy trees by impacting their structure, resilience, and ES provision. Trees that host particular pathogens facilitate their spread throughout a forest, which decreases the monetary and ecological value of the forest from damage. Specific trees host specific pests, so the potential damage of each pest differs depending on location and the tree host species. Monocultures especially encourage the spreading of pests since they provide many adjacent host trees. Pests' fleeting life cycles and extensive dispersal potential makes them effective at inflicting rapid and widespread damage to urban forests. For instance, Chicago trees suffered major mortality from Dutch Elm Disease in the late 20th century and the Emerald Ash Borer (*Agrilus planipennis*) in the early 2000s.

Climate change and urban stressors make urban trees vulnerable to further detriment from pests and pathogens. Restricted city space prevents pests' natural predators, thereby allowing herbivorous pests to proliferate (Raupp et al., 2010). The urban heat island effect also exacerbates dry conditions brought by climate change, which weakens urban trees through drought stress (Mattson & Haack, 1987). More specifically, pests exploit urban trees during drought-stressed episodes by feeding off their increased sugar and nitrogen levels (White, 1984). Generally, a rise in temperature directly correlates with increased pest metabolism and development, leading to larger, more fecund pests (Dale & Frank, 2017). Given the predicted increase in pest feeding and offspring, pests will continue to stretch into more geographic regions, impacting more urban environments along the way. Moreover, climate change intensifies non-native pests' threat to urban trees as pest-predator coevolution is not an option to generate ecosystem resilience under such rapid change. Since there are no existing predators to nonnative pests, trees can suffer from extreme damage before a man-made solution is implemented or a natural solution evolves.

Similar to pests, climate change affects forest pathogens like fungi and bacteria that are extremely deleterious to urban trees. Climate change impacts pathogens by increasing growth and reproduction rates, increasing disease transmission rates, changing dispersal processes, and improving overwinter survival (Simler-Williamson et al., 2019). Climate change may also indirectly cause decreases in urban tree hosts' nutrient statuses and protective resource allocation, increasing their susceptibility to pathogen attacks (Dukes et al., 2009). Pathogens effectively decimate urban trees because they have a fast generation time, enabling them to genetically respond to climate change and environmental modifications faster than their hosts and sustain rapid population growth (Olatinwo et al., 2013). Specific pathogen species' reactions to climate change are difficult to predict due to their varied life cycles (Tubby & Webber, 2010). Secondary pathogens that depend on stressed trees for settlement are expected to burgeon in the drought-like conditions brought on by rising temperatures. Pathogens that depend on moisture, however, are inhibited by the droughts brought by climate change and thus may reduce their harm to urban trees (Vose et al., 2016). To mitigate the undesirable effects that pests and pathogens have on campus trees, UChicago should continue to monitor the changing roles of tree infestations and infections. Additionally, UChicago should continue their integrated approach of investigating and treating infected trees. For more information on specific pests and their threat to UChicago campus trees, refer to the 2020 i-Tree Ecosystem Analysis' detailed synopsis of which pests are closest in proximity to the University.

2.4 Climate Change and the UChicago Campus Forest

2.4.1 Effects on UChicago Trees

Climate change has far-reaching effects, impacting hydrology and water resources, agriculture, human health, ecosystems, and other urban elements. The projected Chicago-area climate trends will not lead to equal outcomes for all UChicago trees: rising temperatures and changing precipitation patterns will likely benefit some tree species while harming others, and some species that are currently not suited to this region's climate may become poised to succeed in the future. Additionally, indirect effects of climate change such as heightened tree pests and diseases, significant runoff and flooding, and increased wind damage (from more frequent severe storms) could differentially impact tree species depending on their unique planted adaptive capacities (i.e., the ability of a tree to adapt to stressors in its lifetime). In a 2017 Chicago urban forest vulnerability assessment and synthesis, Brandt et al. (2017) projected future habitat suitability for trees using species distribution models that combine a low and high emissions scenario. Brandt found that, by the end of the century in the Chicago region, the suitable habitat for 11 primarily northern tree species may decrease and the suitable habitat for 25 species may increase, while 15 species may gain a newly suitable habitat. Brandt also found that invasive tree species have some of the highest capacities to adapt to a range of stressors, and that 77% of individual trees with low climate change vulnerability are invasive species. 17% of the tree species currently present in the Chicago region have moderate-high or high vulnerability to climate change.

Table 5 synthesizes information about expected climate change outcomes for selected tree species at UChicago based on the 2020 i-Tree report's Importance Values (IV) and Facilities Services' (FS) interest. i-Tree Eco assigns an IV to each campus tree species by summing the species' percent population and percent leaf area on campus (University of Chicago's *i-Tree Ecosystem Analysis*, 2020). This calculation privileges the most dominant species on campus as the most "important." Notably, i-Tree states that they are not promoting additional plantings of "important" tree species. The ten species with highest IV comprise 43.4% of trees on campus and 53.3% of total tree leaf area. Studying the potential climate impacts on these trees is thus essential for predicting how a large proportion of the campus forest may change and where replacement will likely need to occur. FS' interest refers to tree genera that FS would like to know more about and/or plant more of (Representative of Facilities Services, personal communication, August 9, 2021). There is considerable overlap between the i-Tree and FS metrics, so this table can be used to assess campus forest climate resilience both for the already-dominant trees and the potential new plantings. Trees are represented in the table at the species level because, within a genus, different species have different values for each variable assessed (hardiness zone, planted adaptation class, etc.).

Each column in the table is a metric for assessing and predicting a tree species' suitability for future climate conditions in Chicago, IL. The first variable is the potential effect of plant hardiness and heat zone changes on habitat suitability, since comparing current hardiness and heat zone ranges of tree species to future zone projections helps predict how a species' habitat may be impacted by future temperatures (Brandt et al., 2017a). The "planted adapt class" variable is a measurement given to tree species based on a score that evaluates their ability to withstand stressors in planted and urban environments. Brandt et al. (2017a) analyze each tree species by examining disturbance and biological factors. Disturbance factors include disease, pests, browse (i.e., impact of animal grazing on vegetation), drought, flood, ice, wind, temperature gradients, air, soil, water pollution, and salt. Biological factors include competition, light, edaphic specificity (i.e., soil requirements like pH, texture, and thickness), restricted rooting conditions, soil compaction, nursery production potential, planting establishment, required maintenance, and invasive potential. Based on the first two variables, Brandt et al. (2017a) project an overall climate change vulnerability score for each tree species under a high emissions scenario that assumes a continuing rise in carbon and methane emissions. Trees are grouped into 5 categories: low, low-moderate, moderate, moderate-high, and high. The last variable, Wuebbles et al.'s (2021) ecoregion "capability rankings," is an alternate measure of success in a future climate. UChicago is located in the "Southwestern Great Lakes Morainal" ecoregion, and "capability" is a measure of a species' ability to withstand projected climate changes given their current abundance, adaptability, and habitat suitability under a high carbon emissions scenario.

Zone changes are only set to impact two dominant campus trees: the green ash (*Fraxinus pennsylvanica*) tree is projected to respond negatively to zone changes, while the slippery elm (*Ulmus rubra*) tree is expected to respond positively. As for trees of interest to FS, the Amur maple (*Acer ginnala*) is at risk to zone changes while the common baldcypress (*Taxodium distichum*), Kentucky coffeetree (*Gymnocladus dioicus*), northern red oak (*Quercus rubra*), shingle oak (*Quercus imbricaria*), and dawn redwood (*Metasequoia glyptostroboides*) are predicted to thrive. The remaining trees in the table were excluded from Brandt et al.'s analysis due to missing model information. While green ash trees (*Fraxinus pennsylvanica*) are no longer planted due to their risk from the Emerald Ash Borer (*Agrilus planipennis*) and their invasive traits, they should be monitored along with Amur maples (*Acer ginnala*) (a total of 174 trees) as lower/colder hardiness zones move northward. Trees with positive rankings can potentially be favored in planting considerations, though they should be first assessed with every climate metric.

There are no dominant UChicago campus trees with low adaptability scores for placement in planted areas or urban environments. The northern catalpas (*Catalpa speciosa*), however, are at risk due to low adaptability. These 25 trees should be monitored for stress and mortality. All other trees evaluated are split roughly evenly between medium and high adaptability scores, indicating that campus trees are adequately prepared to withstand changes in climate conditions.

There are no dominant UChicago tree species labeled above moderate climate change vulnerability; all are ranked between moderate to low vulnerability. Of the species of interest to FS, northern catalpas (*Catalpa speciosa*) and Amur maples (*Acer ginnala*) (36 total trees) are of moderate-high vulnerability to climate change. This categorization reflects the climate risk to these two species demonstrated by other columns within Table 5. This summative metric reassures that most UChicago campus trees are not in critical danger to Chicago region climate change. However, dominant tree species tagged as moderate vulnerability (green ash (*Fraxinus pennsylvanica*) and Norway maple (*Acer platanoides*)) should have the highest priority for examination over the next 50 years, regardless of the fact that more plantings are not desired. Removing undesirable trees before their natural death can breach the LPP (Section A.1: Carbon Storage and Sequestration), thereby rendering trees carbon sources.

As for capability rankings, American elm (*Ulmus americana*), slippery elm (*Ulmus rubra*), northern hackberry (*Celtis occidentalis*), honeylocust (*Gleditsia triacanthos*), silver maple (*Acer saccharinum*), and northern red oak (*Quercus rubra*) all have high rankings for this ecoregion, meaning that these species are expected to cope well with current climate change projections. The American linden (*Tilia americana*) and red maple (*Acer rubrum*), both of interest to FS, are predicted to fare "very poorly" and "poorly," respectively. These two species, comprising 119 trees on campus, should be monitored closely.

Overall, the dominant UChicago campus trees are expected to fare well in future climate change scenarios. Some species of interest to FS (e.g., northern catalpas (*Catalpa speciosa*), Amur maples (*Acer ginnala*), American lindens (*Tilia americana*)) should be continually assessed to prevent widespread mortality and to efficiently prepare for future plantings. There are 129 total species of trees on campus and applying these four climate metrics to the remaining species would give a stronger picture of the total campus forest climate risk. While not all campus species are listed in the Brandt et al. (2017a) and Wuebbles et al. (2021) analyses, assessment of any species contributes to a more comprehensive succession planning effort. To effectively plan for the success and care of campus trees, UChicago should continue to analyze future climate projections while also taking seasonal climate changes, soil conditions, and precipitation into consideration when selecting new trees for planting.

Family, Genus Botanical Name	Species Common Name	Heat / Hardiness Zone Effect*	Planted Adapt Class*	Climate Change Vulnerability*	Capability Ranking**
Bignoniaceae, Catalpa	catalpa, northern 🌲 (25)		Low	Moderate-High	
Cannabaceae, Celtis	hackberry 🌳🌲 (117)		High	Low	Good
Cupressaceae, Metasequoia	redwood, dawn 🌲 (13)	Positive	Medium	Moderate	
Cupressaceae, Taxodium	baldcypress, common 🌲 (16)	Positive	High	Low	
Fabaceae, Gleditsia	honeylocust, common thornless 🌳🌲 (470)	No Effect	Medium	Low-Moderate	Good
Fabaceae, Gymnocladus	coffeetree, Kentucky 🌲 (63)	Positive	High	Low	
Fagaceae, Quercus	oak, bur 🌳🌲 (93)		High	Low	
Fagaceae, Quercus	oak, chinkapin 🌲 (13)		Medium	Moderate	
Fagaceae, Quercus	oak, northern red 🌲 (91)	Positive	Medium	Moderate	Good
Fagaceae, Quercus	oak, shingle 🌲 (26)	Positive	High	Low-Moderate	
Fagaceae, Quercus	oak, swamp white 🌳🌲 (132)		High	Low-Moderate	
Ginkgoaceae, Ginkgo	ginkgo 🌳🌲 (69)	No Effect	High	Low	
Malvaceae, Tilia	linden, American 🌲 (32)		Medium	Low-Moderate	Very Poor
Malvaceae, Tilia	linden, littleleaf 🌳🌲 (162)		High	Low	
Oleaceae, Fraxinus	ash, green 🌳 (163)	Negative	Medium	Moderate	Fair
Platanaceae, Platanus	planetree, London 🌲 (24)	No Effect	Medium	Moderate	
Sapindaceae, Acer	maple, Amur 🌲 (11)	Negative	Medium	Moderate-High	
Sapindaceae, Acer	maple,	No Effect	High	Low	

	freeman 🌳🌲 (63)				
Sapindaceae, Acer	maple, hedge 🌲 (41)		High	Low	
Sapindaceae, Acer	maple, Norway 🌳🌲 (125)	No Effect	High	Moderate	
Sapindaceae, Acer	maple, red 🌲 (87)		Medium	Low-Moderate	Poor
Sapindaceae, Acer	maple, silver 🌲 (66)		Medium	Low-Moderate	Good
Sapindaceae, Acer	maple, sugar 🌲 (77)		Medium	Moderate	Fair
Ulmaceae, Ulmus	elm, American 🌳🌲 (32)		Medium	Low-Moderate	Good
Ulmaceae, Ulmus	elm, Siberian 🌳🌲 (92)		Medium	Low-Moderate	

* Brandt et al., 2017a
** Wuebbles et al., 2021
🌳 Top 10 i-Tree "important" species
🌲 Genus of interest to FS

Table 5: Projected Impacts of Climate Change on Selected Tree Species at UChicago. *Each species is listed along with its frequency on campus. No species with fewer than 10 trees on campus is included in this table due to its small proportion of the forest; assessing such species would not give a representative picture of how the whole campus forest may fare with climate change. Lighter colored data cells indicate a more protective or positive classification, while darker red cells indicate a more at-risk or poor classification. Dark gray data cells indicate missing or insufficient information regarding a tree species and the corresponding variable (column head). Elm species, reported in the 2020 i-Tree Ecosystem Analysis as elm spp, are here separated as American elm (Ulmus americana) and Siberian elm (Ulmus pumila) to show individual species predictions (slippery elm (Ulmus rubra) are not included because there are fewer than 10 on campus and the remaining elm hybrid cultivars are not defined in i-Tree and therefore cannot be listed individually). Other elm species are not included due to insufficient data.*

Given that trees in urban environments already face many stressors like disruptions from construction, poor soil quality, air pollution, the urban heat island effect, and invasive species, the direct and indirect impacts of climate change could cause disaster for vulnerable tree species. Even for species that are not predicted to be significantly threatened by climate change (like the majority of UChicago's most prevalent trees), nothing is certain—climate change projections are only as good as the models that produce them, which can never predict the future with complete accuracy. Additionally, widespread land conversion of Chicago and Illinois has degraded large portions of native habitats, inhibiting the ability of trees to respond to rapid climate changes (Wuebbles et al., 2021). Generally, urban forests with high species, genetic, and age class diversity are more resilient to the effects of climate change (Brandt et al., 2017b), and considerations can be made to select tree species that are most suitable to Chicago's projected climate and hardiness zones to ensure a robust and resilient campus forest. Species adapted to climate zones south and southeast of Illinois may be favored, since Illinois' projected warming models the current conditions of these areas (Union of Concerned Scientists, 2009). Planting initiatives should also continue to prioritize species that are more tolerant to urban conditions and extreme weather. Finally, having sufficient organizational, technical, social, and economic resources in urban forest management is crucial (Brandt et al., 2017b). The authors note that larger financial investments in tree planting and maintenance (e.g., purchasing trees, supplementing soils, pruning, etc.) are necessary to support a healthy urban forest and its services long-term.

2.4.2 Effects on UChicago Tree Ecosystem Services

Not all of UChicago trees' ecosystem services are equally impactful (see Section 1.3: Ecosystem Services at UChicago). Additionally, not all ES are equally robust to the effects of climate change. The literature on climate change and ecosystem services is limited, so complete assessments of each ES on campus are not possible. However, some likely impacts do emerge from the past decades of modeling and research studies. Based on the general trends observed and predicted for urban forests, our assessments for the future of UChicago campus ES are as follows. For more detailed explanations of carbon storage/sequestration, microclimate regulation, human health benefits, and habitat provisions and functions, see Appendix B.

Carbon storage and sequestration will likely increase in the next few decades due to increased warming and nitrogen deposition favoring tree growth. However, water stress and a surpassed threshold of species-specific suitable temperatures will lead to a net decrease in carbon storage/sequestration beginning around 2040-2070, depending on models. Shortened lifespans of trees will increase the likelihood of reaching the LPP (as defined in Section A.1: Carbon Storage and Sequestration), such that energy spent planting and maintaining trees will not be paid back in carbon benefits. The University's trees do not presently provide significant carbon benefits compared to total carbon emissions, but future climates will render trees more of a carbon source than a carbon sink.

Air pollution mitigation will likely continue to be an impactful ES at the University. Pollution levels will likely rise with increased urban industry, and trees are vital to improving local air quality. At first, increased tree growth from raised temperatures may occur, leading to more pollution alleviation. However, researchers expect climate change to decrease canopy areas, which will reduce total pollution mitigation per tree. High pollution concentrations can block stomata and prevent continued pollution deposition, also lowering individual tree pollution mitigation. Air pollution mitigation will likely be strained in the future but will continue to be a crucial campus ES.

Stormwater runoff management depends highly on urban stressors in addition to climate change, like poor soil quality and soil compaction. Trees' established root systems are beneficial to stormwater infiltration and may be threatened by soil erosion caused by future disrupted soil biogeochemical cycling. Management from canopy interception loss and evapotranspiration may suffer from decreased canopy area in urban environments. Increased prevalence of severe weather events (e.g., storms, floods), as well as predicted increases in Midwest precipitation due to warm air holding more moisture, render stormwater management an impactful ES for the campus future, though one that may decrease in impact due to canopy reduction and root damage.

Microclimate regulation will continue to be an impactful ES at the university due to the rising intensity of Chicago's urban heat island. Due to projected urban warming of 1.64ºF each decade (Voogt, 2002, as cited in Corburn, 2009), UChicago's trees will be crucial in shading pedestrians and lowering surface temperatures. Urban heat may boost tree growth in the next few decades, helping cities stave off temperature increases with cooling and shading. However, urban stressors (e.g., poor soil quality, soil compaction, excessive heat, high pollution concentrations), coupled with water stress, extreme weather events, and consistently higher temperatures will likely cause eventual tree dieback and mortality, and thus decrease the area shaded by canopies. UChicago may ameliorate water stress with irrigation provided by FS, though this poses a tradeoff with water use sustainability goals. Overall warming may still hinder tree canopy and branch growth and thus lower the efficacy of microclimate regulation on campus. The tree microclimate ES is both increasing in significance and becoming more difficult for trees to provide.

Building energy effects is an ES that will respond to the same future changes as microclimate regulation. Initial growth bursts from higher temperatures may eventually be outweighed by city and climate stressors that decrease canopy area and minimize growth. With decreased tree canopies, shading and evapotranspiration will be lessened in the summer, causing buildings to use more energy and resources on air conditioning. In the winter, however, lack of building shading allows more solar radiation to hit and heat buildings, lowering the energy load for heating. However, winters will also be warming, lessening the intensity of needed heating. Climate change may therefore cause increased UChicago greenhouse gas emissions in summers and decreased emissions in winters.

Noise attenuation will likely increase in the next few years from CO_2-, nitrogen-, and warming-stimulated tree growth. However, studies predict that the combination of urban and climate change stressors will decrease canopy area in the long-term and thus decrease the amount of tree biomass reflecting and absorbing sound. As a result, the campus soundscape may become louder in the future.

Habitat provision and functions are one of the more nuanced areas of climate change research. As trees grow rapidly due to warming in the next few years, the creatures which inhabit those trees may similarly grow in number due to increased habitat availability. However, tree range shifts and unsuitability to future climates can cause rapid loss of habitat area, causing trophic cascades (i.e., effects of predators that propagate downward through food webs across multiple trophic levels (Ripple et al., 2016)) and ecological disturbances. Without a full inventory of UChicago's animal inhabitants, it is unclear which animals will continue to be well-suited to the Chicago environment, and which ones will experience range shifts or mortality. It should be considered that non-tree plants, animals, and microorganisms on campus will also likely be affected by changing climates independently of trees, though trees will modulate the environment. Wherever trees are located, they will continue to provide beneficial habitat functions as keystone structures.

Human health benefits is a less well-quantified ES, and its relation to climate change needs further study. Many of the mental health benefits of trees result from the presence of green space, which will likely persist in future climate scenarios. Health benefits are positively associated with the presence of larger trees, and large trees are predicted to suffer higher mortality in future climates due to water and nutrient constraints. Additionally, tree mortality from climate and urban stressors may decrease human presence in public outdoor spaces, providing conditions more conducive to crime, though the correlation between nature and violence is still debated. The effects of climate change on physical health (e.g., cardiovascular, neurological, respiratory) and community health (e.g., social cohesion) are less well-studied but will likely persist with tree presence. In general, the health benefits of trees will likely remain in future climate scenarios, and potentially increase in impactfulness as stress associated with both direct climate impacts (like extreme weather) and indirect climate impacts (like the mental burden of an existential threat) rise (Wuebbles et al., 2021).

Aesthetic quality improvement is a highly subjective ES and is dependent on people's affinity for individual trees and tree species. Some tree species are not predicted to be suited to Chicago's future warmer climate, and may be reduced in number on campus, causing individual emotional responses. Additionally, average tree sizes may decrease due to the predicted loss of large trees. However, it is highly likely that the University will maintain a strong tree presence on campus in any climate scenario, creating green space and maintaining the University's traditional gothic aesthetic. Thus, the ES of aesthetics will likely persist despite climate change.

Oxygen production is an ES deemed relatively unimpactful on the UChicago campus due to the abundance of oxygen in the atmosphere (as discussed in Section 1.3.3: Least Impactful ES). While immediate tree growth and future tree loss would respectively create more and less oxygen, the overall impact on the environment is negligible. Climate change is not likely to impact atmospheric oxygen production ES on a global scale, though it may minimally affect local oxygen quantities.

Figure 3 summarizes the predicted increases and decreases in ES provision by campus trees in a changing climate. In general, many of the net future ES effects will likely be negative due to decreased canopy cover and increased mortality rate (carbon storage and sequestration, air pollution mitigation, stormwater runoff management, noise attenuation, urban microclimate regulation, oxygen production). Human health improvement is one ES predicted to increase in significance, while habitat provisions and functions and aesthetics will persist at the same level. Building energy effects may uniquely increase in the winter and decrease in the summer from a loss of canopy area and resulting shading. Making informed tree and location selections and continuing proper tree maintenance will ensure that the campus forest will persist in providing as many ES as possible.

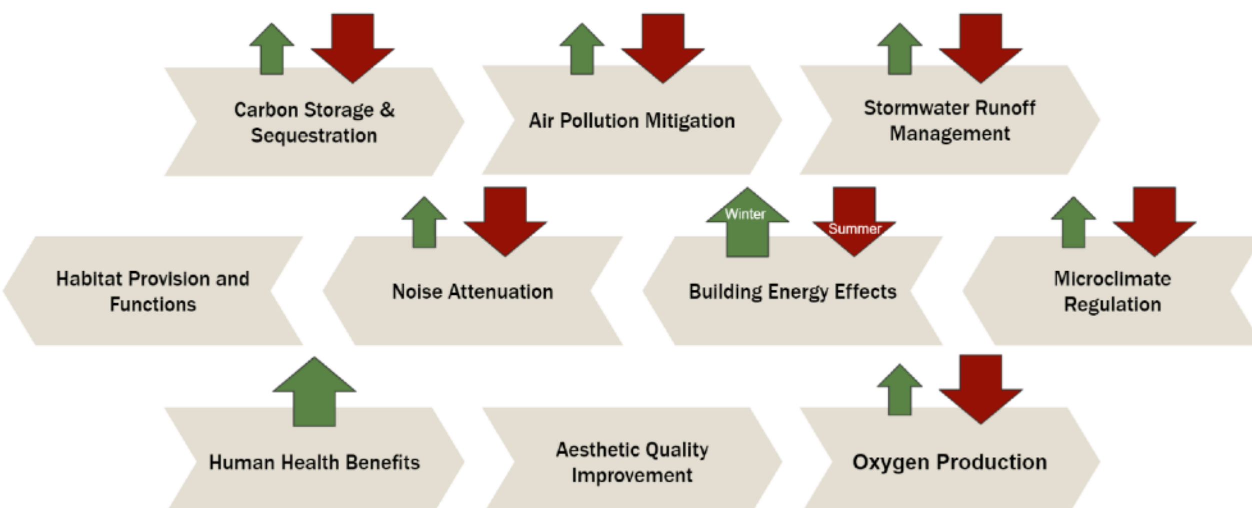

Figure 3: Predicted Impacts of Climate Change on Campus Ecosystem Services. *Green up arrows represent increases in ES provision. Red down arrows represent decreases in ES provision. No arrow(s) indicates no change to the ES (i.e., continuous provision of the ES). The presence of smaller green up arrows and larger red down arrows demonstrates an initial increase in ES provision (accompanying initial tree growth) but an eventual decrease in ES provision (accompanying long-term climate and urban stress).*

2.4.3 Climate Change Evaluation Methods

The literature about how climate change may affect Chicago and its trees, though data-driven, is only a projection of how our University's forest will fare in a changing climate. Data on the changing state of trees on our campus is needed to supplement these predictions and enable the University to protect its trees and their valuable ES.

We recommend that the University track climate data (temperatures and extreme weather) from local weather stations and continue to note tree conditions (percent die-back, presence of pests, etc.) for each tree or a representative random sample of trees on campus. Such data would enable University-specific analyses of tree changes with local climate. Using location data for each tree, trees may be matched to corresponding information from the UChicago 2020 Tree Inventory data (if they were planted prior to the most recent inventory). This method will supplement existing tree inventory data, enabling more varied tree analyses (e.g., time-series). Using the inventory as a baseline will give insight on how individual trees have changed with respect to time and climate conditions. Further comparison with other information provided by the inventory (species, age, location, etc.) can aid in finding and addressing categoric susceptibilities of campus trees to climate change. Section 3: Succession Planning will discuss how such measures may be applied to existing tree planting considerations at the University.

2.5 Conclusion

Climate change is predicted to impact the global environment in numerous ways. UChicago must be aware of and prepared for potential climate change effects on its campus trees in order to most effectively support its urban forest. Trees' ability to provide valuable ecosystem services may decline with rapid warming, changing drought patterns, and extreme weather, though it depends on the individual species and service. Chicago's projected warming is predicted to cause a northward shift in hardiness zones and an increase in urban forest susceptibility to pests and pathogens, while warming temperatures and increasingly extreme weather events will exacerbate stress on UChicago's campus forest. However, tree species will not be affected equally by predicted conditions: some species are poised to become more successful as other species suffer. Since changes in forest health will affect the provision of ES by campus trees, climate change must be considered when evaluating current and future ES priorities. Due to the complexity of ways in which UChicago trees may be impacted by climate change, we recommend that the University begin supplementing research-based projections and existing tree inventories with more campus data on climate and tree conditions. Additional information on individual and categoric susceptibilities of campus trees to climate change will aid in understanding the University's forest health and how it may be maintained and improved by future tree planting.

3. Succession Planning

3.1 Introduction

Facilities Services (FS) at the University of Chicago plans and maintains the University's grounds, including its 3,764 trees. As a matter of course, some trees must be removed annually due to damage or mortality from extreme weather, infection, and maturity. Planning for the replacement of those trees, often referred to as "succession planning," is a crucial and highly deliberated process. Effective succession planning upholds the structural and functional values of a forest and prepares the landscape for future challenges like pest/disease outbreaks, climate change, and human activity (e.g., construction, shifting landscape priorities) (Warriner, 2010). Current UChicago succession planning procedures do not explicitly incorporate tree ecosystem services (ES) (i.e., the positive provisions of trees for human wellbeing) beyond aesthetics and stormwater management, nor climate change projections for Illinois and Chicago. Based on considerations outlined in the previous two sections, we recommend that a comprehensive UChicago forest succession plan incorporates both ecosystem services and climate change in order to most effectively maintain the campus forest as a functional and beautiful aspect of the University.

In this section, we begin with a contextualization of ecosystem-based adaptation. We then briefly outline the history of the University's and Chicago's tree landscapes, including relevant monocultures and diseases. Using the 2020 inventory data collected by Bartlett Tree Experts, we present maps, graphs, and other visualizations of the campus forest's age, species, condition, and diversity distributions. We next discuss the current flow of succession planning considerations and make recommendations for where to incorporate ES and climate change. Table 6 presents FS with species (and their characteristics) that are well-suited to Chicago's changing climate. We conclude with a synthesized list of recommendations that center on improving the resilience and benefits of the University's forest.

3.2 Ecosystem-Based Adaptation

As climate change threatens urban forests, many cities and institutions have adopted a practice known as "ecosystem-based adaptation," defined as the "use of biodiversity and ecosystem services as part of an overall adaptation strategy" (Secretariat of the Convention on Biological Diversity, 2009). Harnessing trees as ES-providers can be used to the benefit of both humans and the natural environment and can be established in succession planning practices. One main strategy in ecosystem-based adaptation is planning for resilient urban forestry (Wamsler et al., 2016), which the University can directly work towards by considering climate change projections when selecting new trees for planting. Forest resiliency in a changing climate is highly dependent on functional diversity and species composition; many recommendations center on planting and maintaining diverse species with varying growth rates, physiologies, and phenologies (Ordóñez & Duinker, 2014). Wamsler et al. (2016) emphasize that adaptation strategies should be "integrated into existing operations, planning, and decision-making mechanisms" rather than be viewed as "extra considerations to be added on or weighed against others" in an effective management strategy. The following research and data-based recommendations build on this framework of adaptation integration, in effect strengthening University tree management for a resilient future forest.

3.3 History of UChicago and Chicago Forest Management

A brief historical review of the University of Chicago's urban forest management, as communicated by a representative of Facilities Services (personal communication, June 24, 2021) and the City of Chicago's urban forest management illuminates current tree practices and goals. Since the University of Chicago's founding in 1890, the campus landscape has been modified multiple times to fit the visions of many planners, landscape architects, and Trustees, many of which are detailed in the minutes from historical meetings. In the late 1800s, architects intended to implement formal rows of trees by planting mature oaks (*Quercus*) due to their grand appearance and collegiate aesthetic. These formal rows were expected to give a professional ambiance to the University; however, landscape architect Ossian Cole Simonds hoped to adopt a whimsical style in his 1901 master plan instead. Trustees did not favor a naturalistic campus over an ordered one, and the University eventually settled on a new plan proposed by brothers John and Frederick Jr. Olmsted in 1902. In their preliminary vision, the Olmsted brothers included trees planted along formal allées and sidewalks. This new design, however, was based on replacing oak (*Quercus*) and honeylocust (*Gleditsia*) trees with an elm (*Ulmus*) monoculture. Elm (*Ulmus*) trees were regarded as the perfect species for urban environments since their tall height and wide canopy provided plentiful shade. About twenty years after installation, elm (*Ulmus*) trees were identified as susceptible to infestation by insects. Despite these cautions, the Olmsted Brothers retained their original plans for elm (*Ulmus*) trees on the basis that other tree species would likely also develop their own pest hindrances (that is, the idea that all species will eventually be vulnerable to some pest). In the early 1970s, a majority of the campus elm (*Ulmus*) trees succumbed to Dutch elm disease. Dutch elm disease is a fungus transmitted by bark-beetles or through root grafts of nearby infected elm (*Ulmus*) tree species (Karnosky, 1979), and, like all pathogens, is spread quickly by a monoculture. The disease is incredibly lethal to American elms *(Ulmus americana)* and has decimated about 40 million elms (*Ulmus*) throughout the country (D'Arcy, 2005).

The city of Chicago's urban forest has been under scrutiny for decades, mostly due to a lack of planting trees when others are removed, as well as a heavy reliance on gray infrastructure (i.e., structures "designed to move urban stormwater away from the built environment," including gutters, drains, and other collection systems ("Why Consider Green Stormwater Infrastructure," 2021)) (Scott et al., 2020). In the late 1990s, however, the city began to shift its focus to prioritizing greenspaces and developing solutions to climate projections (e.g., green infrastructure). Researchers have identified that Chicago can maximize the benefits of its urban trees through sustained maintenance, and accordingly recommend new policies and programs like urban forest stewardship and yard-tree planting partnerships (McPherson et al., 1994). Additionally, researchers recognize that topics such as microclimates and BVOC emissions need more attention. The city of Chicago has since taken numerous steps towards maintaining its urban forest, including conducting tree censuses, developing environmental action agendas, publishing frameworks to protect natural forests, and utilizing i-Tree to analyze ecological functions of trees (City of Chicago, 2009). In its most recently established urban forest agenda (City of Chicago, 2009), the city of Chicago includes a detailed management plan that incorporates several recommendations on conserving and expanding its urban forest while promoting green infrastructure and forest stewardship. The University of Chicago has adopted a similar sustainable agenda in recent years, including upholding the urban forest by pursuing Tree Campus USA certification and conducting tree censuses with Bartlett Tree Experts. Reviewing

Chicago's historical and recent environmental actions contextualizes the current state of regional forest management and can inspire sustainable actions on a local, campus scale.

3.4 Current State of the UChicago Forest

In devising our succession planning recommendations, we explored the current state of UChicago's forest, including tree ages, conditions, and species distributions as identified in the UChicago 2020 Tree Inventory conducted by Bartlett Tree Experts. We then determined potential forest vulnerabilities by relating the inventory data to future climate challenges outlined in Section 2: Climate Change.

3.4.1 Forest Age and Condition Spatial Distributions

The UChicago 2020 Tree Inventory categorized campus trees into five age classes: "new planting," "young," "semi-mature," "mature," and "over-mature." The only class which inherently raises concern if largely present is "over-mature." The condition classes include "good," "fair," "poor," and "dead." Poor and dead classes inherently raise concern if largely present. Bartlett's definitions of age and condition classes are included respectively in Tables 8 and 9 in Appendix C. An ideal forest age distribution would have trees in each category. A mixed distribution of ages favors forest resilience because larger, mature trees provide more ES but younger trees are necessary to sustain forest density as old trees die. An ideal condition distribution would have most trees in the "good" class and few trees in the "poor" and "dead" classes, indicating that trees are well-managed and well-matched to local conditions. Minimizing the number of trees that are young or semi-mature in poor and dead age classes is an important aspect of averting the Last Positive Point (i.e., when the carbon emitted in planting and maintaining a tree surpasses the carbon sequestered by the tree itself). Having few younger trees in negative condition classes also indicates a minimal need to replace any prematurely removed trees, which is costly in carbon and finances.

Figure 4 maps all inventoried campus trees by their age class in 2020. The figure shows no notable groupings of a single class. The predominant age classes of campus trees are semi-mature (49.6% of trees) and young (36.9%). Since FS already plants young trees to replace mature trees in spaces where large trees are aesthetically desirable (e.g., the Main Quadrangle), the tree population is generally young and semi-mature. Only two over-mature trees were documented on campus in 2020. Thus, age is not a cause for immediate concern in any campus area.

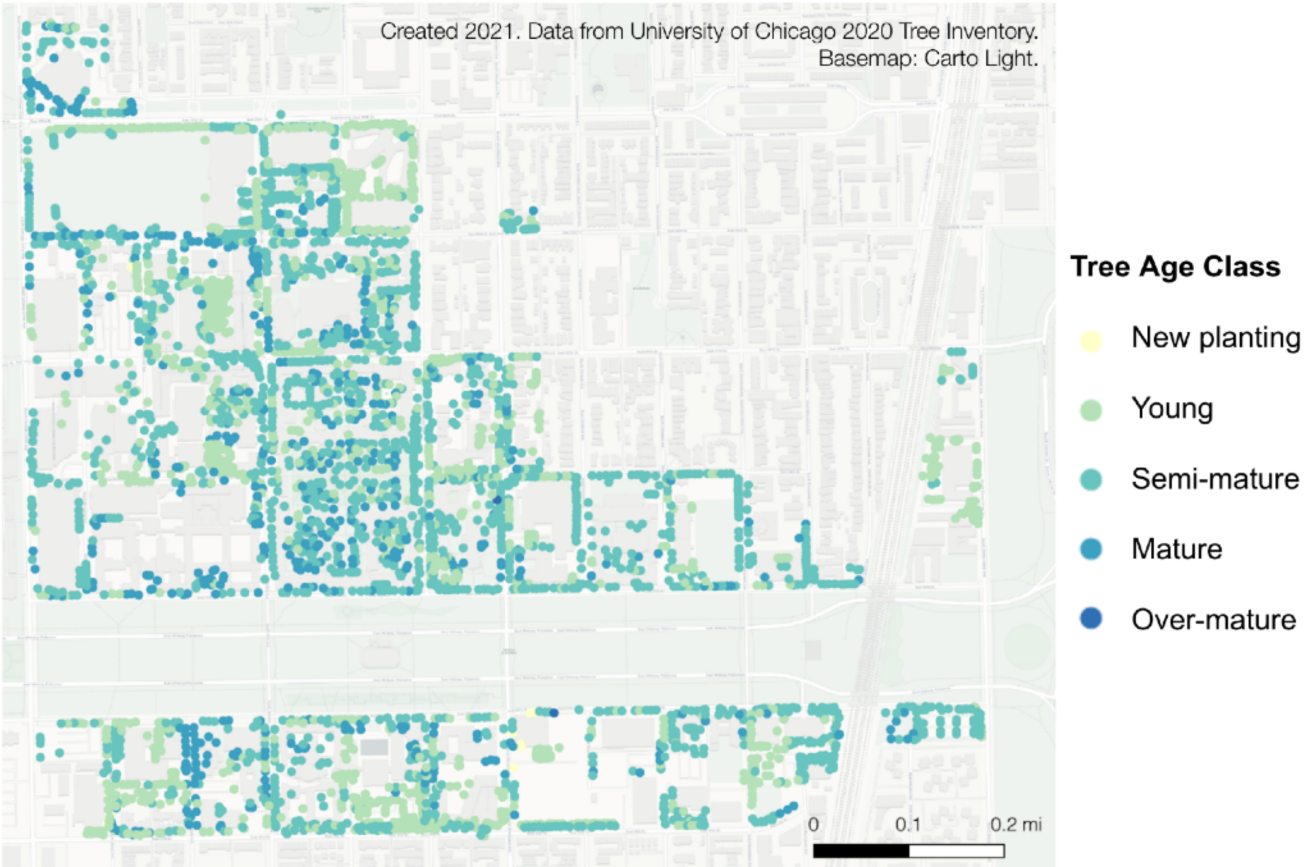

Figure 4: Spatial Distribution of Campus Tree Age Classes. *All trees included in the UChicago 2020 Tree Inventory are represented in this map. Age classes for each tree were determined by Bartlett; their associated definitions are included in Table 8 in Appendix C.*

Figure 5, a map of trees according to Bartlett's condition classes, similarly shows few concentrated spatial vulnerabilities in 2020. Trees throughout campus are predominantly classified as "good" (70.0% of trees) or "fair" (21.6%). Only the "poor" and "dead" classes characterize tree failure, and UChicago had only 316 trees in these categories (8.4% of campus trees) in 2020 (Bartlett Inventory Solutions, n.d.). The overall fair or good condition of campus trees suggests that current tree failure is relatively low; the University should aim to maintain this distribution as climate change poses additional challenges to campus forest health.

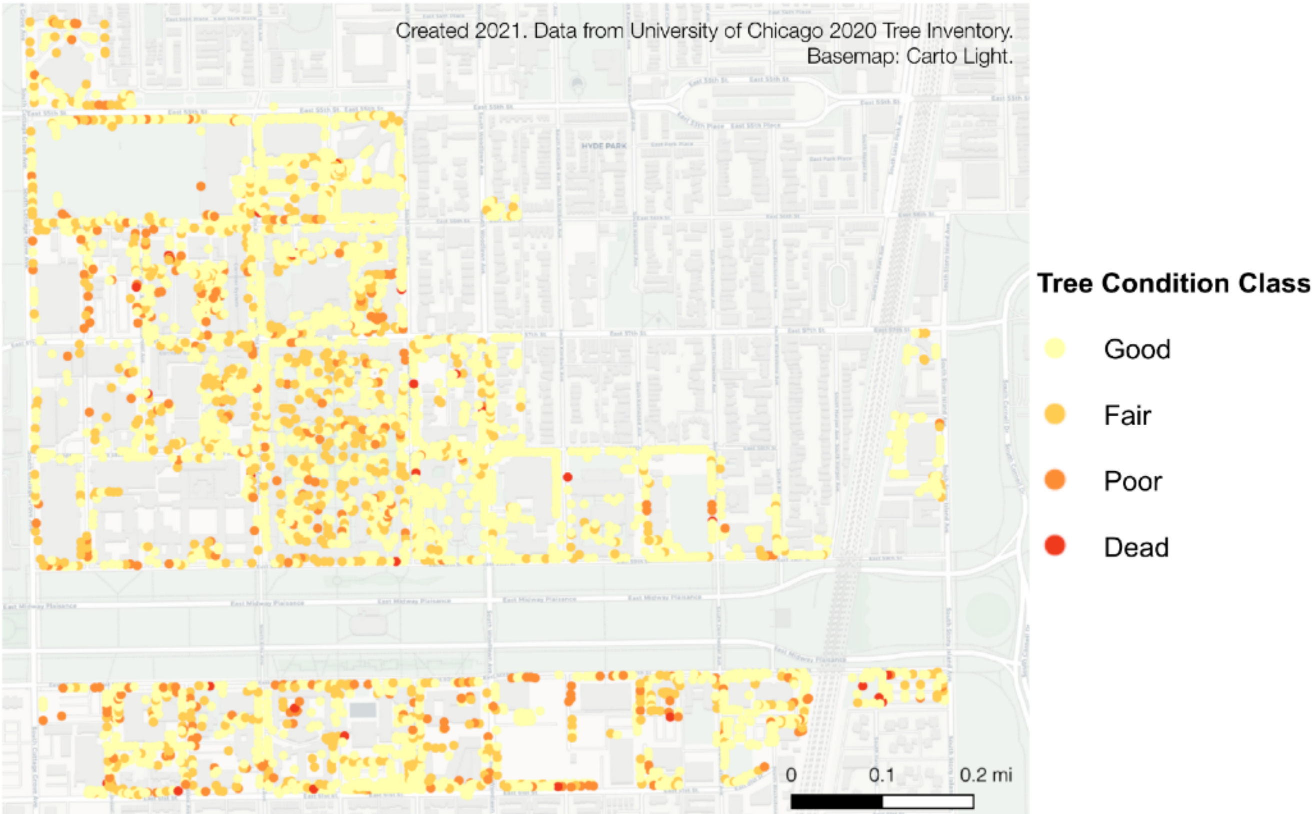

Figure 5: Spatial Distribution of Campus Tree Condition Classes. *All trees included in the UChicago 2020 Tree Inventory are represented in this map. Condition classes for each tree were determined by Bartlett; their associated definitions are included in Table 9 in Appendix C.*

3.4.2 Tree Age and Condition Distributions

Species/genus age distributions are a crucial consideration in succession planning because not only are young trees planted to replace mature trees that have died, but the species/genus of those young trees will affect the future campus forest composition. If the current tree makeup of campus is not desired and/or if increasing biodiversity is a goal to favor climate and pest resiliency, assessing the age distribution of trees within each species/genus can enable more effective succession planning. For example, young trees of not-currently-dominant campus species/genera can be planted in areas with many trees of older, dominant/undesired species/genera to transition the campus forest away from a certain composition (e.g., City of Chicago-planted green ash (*Fraxinus pennsylvanica*) trees along parkways). The condition class distribution of tree species/genera on campus is also a necessary factor in succession planning, as it reveals how particular species/genera are performing. Condition distributions provide insight into how trees are faring in response to species/genus-specific challenges like pests and diseases.

<u>"Important" Species</u>

Figures 6 and 7 respectively show the distributions of age and condition classes (determined by Bartlett Tree Experts) among UChicago tree species with the highest Importance Values (IV) as assigned in the 2020 i-Tree Report. Mosaic plots are used to visualize these distributions because they can represent two variables in a multidimensional way (i.e., show both species and age/condition class frequencies to scale). IV are based on the proportion of the total individuals and total leaf area a species comprises; currently the ten most "important" trees comprise 43.4% of trees and 53.3% of leaf area. Even though many of these species are not desirable as future plantings, they make up a dominant portion of the campus forest. Their "importance," therefore, relates explicitly to succession planning in regard to where tree replacement will occur, how soon trees are likely to need replanting, and in what ways the composition of the forest may change as a result.

As shown in Figure 6, over half of the swamp white oak (*Quercus bicolor*), ginkgo (*Ginkgo biloba*), and hackberry (*Celtis occidentalis*) trees on campus are young, as well as a sizable portion of freeman maple (*Acer freemanii*) and bur oak (*Quercus macrocarpa*) trees. This indicates that, barring individual tree mortality, the future campus forest will have high numbers of these trees. Bur oaks (*Quercus macrocarpa*) and honeylocusts (*Gleditsia triacanthos*) have the highest proportion of mature trees, which indicates that many will likely be replaced within the next few decades. Green ash (*Fraxinus pennsylvanica*) and Norway maples (*Acer platanoides*) are two species FS is currently transitioning the UChicago campus away from due to their susceptibility to pests and diseases, structural growth patterns, and invasive tendencies (Representative of Facilities Services, personal communication, August 10, 2021). Their low proportion of mature trees suggests that this transition is not likely to occur fully in the coming years (even accounting for climate vulnerability), as removing trees before they are mature can surpass the LPP (Last Positive Point, as defined in Section A.1: Carbon Storage and Sequestration), meaning that a tree's maintenance emitted more carbon than the tree itself sequestered.

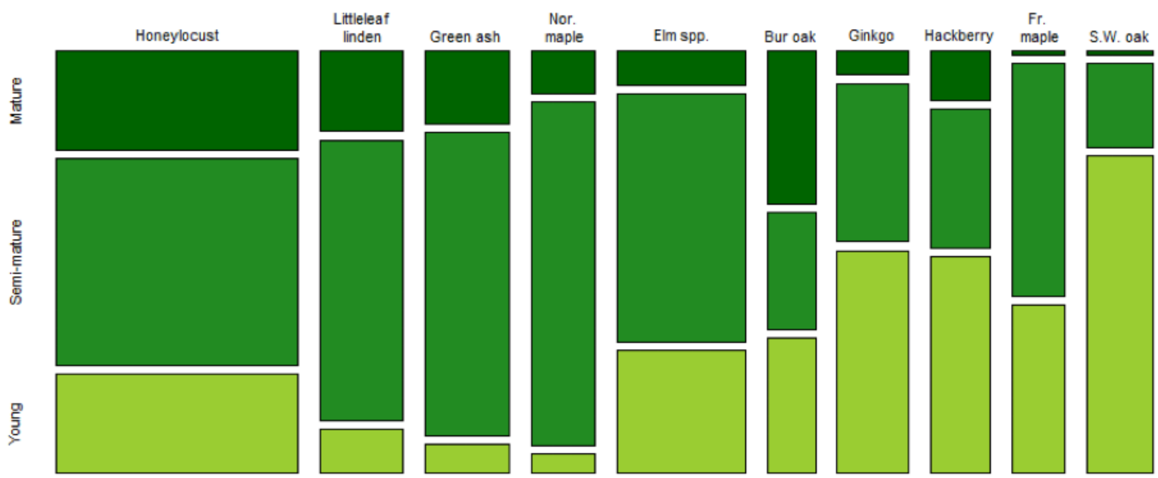

Figure 6: "Important" Tree Species by Age Class. *New planting and over-mature categories (6 trees) are omitted because they contain few trees and would not be easily readable in the figure. Honeylocust species is thornless common (Gleditsia triacanthos var. inermis). Elm spp. includes elm (hybrid cultivars), American elm (Ulmus americana), and Siberian elm (Ulmus pumila). See Table 11: "Important" Tree Species by Age Class for bar values and Table 10: Campus Frequency of "Important" Tree Species in Appendix C for counts of each species on campus. Bar widths are proportional to the number of trees of each species; bar heights are proportional to the amount of trees within a variable category assessed across species. The area of each box is proportional to that tree type's frequency (e.g., young honeylocust (Gleditsia).*

Figure 7 illustrates that the majority of UChicago trees with high IV's are in good or fair condition, indicating that much of the campus forest is in at least moderate health. Ginkgo (*Ginkgo biloba*), freeman maple (*Acer freemanii*), and swamp white oak (*Quercus bicolor*) trees have the lowest proportion of poor condition trees, in addition to their low proportion of mature trees mentioned above. These two factors indicate that these three dominant species are likely to maintain their presence on campus. Norway maple (*Acer platanoides*), green ash (*Fraxinus pennsylvanica*), elm (*hybrid cultivars*), bur oak (*Quercus macrocarpa*), and hackberry (*Celtis occidentalis*) trees have the highest proportion of poor condition trees, meaning that some of these trees may soon need replacement. The lesser overall health of Norway maple (*Acer platanoides*) and green ash (*Fraxinus pennsylvanica*) trees provides further support for the decision to transition the campus away from these species. However, as the majority of Norway maple (*Acer platanoides*) and green ash (*Fraxinus pennsylvanica*) trees on campus are not mature, they should still be cared for throughout their lifetimes. Extra maintenance may be required to improve the health of these species and prevent more trees from falling into poor condition and needing premature, carbon-costly removal.

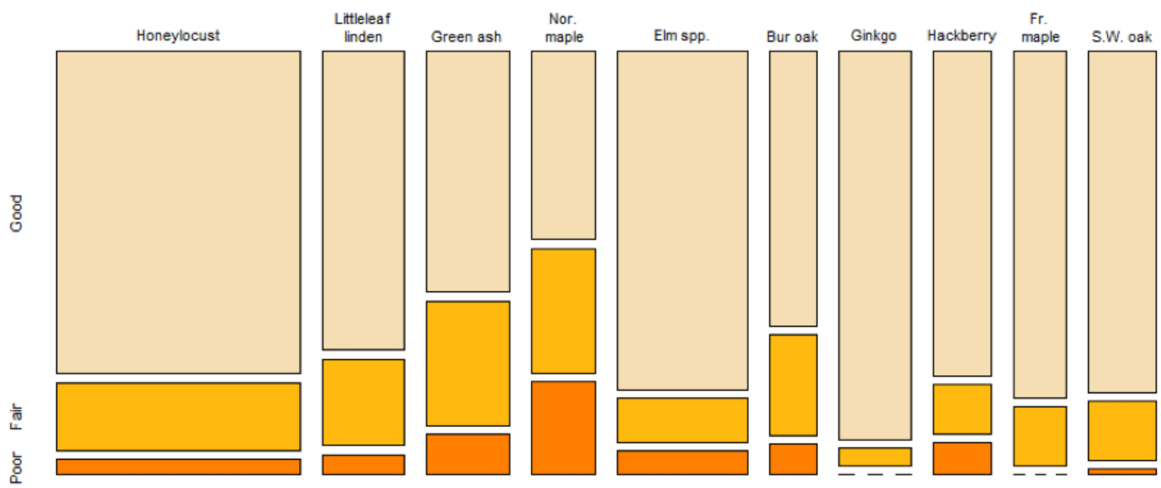

Figure 7: "Important" Tree Species by Condition Class. *Dead condition class is omitted (12 trees) because it contains few trees and would not be easily readable in the figure. Honeylocust species is thornless common (Gleditsia triacanthos var. inermis). Elm spp. includes elm (hybrid cultivars), American elm (Ulmus americana), and Siberian elm (Ulmus pumila). See Table 12: "Important" Tree Species by Condition Class for bar values and Table 10: Campus Frequency of "Important" Tree Species in Appendix C for counts of each species on campus. Bar widths are proportional to the number of trees of each species; bar heights are proportional to the amount of trees within a variable category assessed across species. The area of each box is proportional to that tree type's frequency (e.g., young honeylocust (Gleditsia)).*

<u>Genera of Interest</u>

Figures 8 and 9, respectively, show the distributions of age and condition classes among UChicago genera of interest to FS, which are tree genera that FS would like to assess the presence of and/or plant more of on campus (Representative of Facilities Services, personal communication, August 9, 2021). There is some overlap with the high IV species: coffeetree (*Gymnocladus*), maple (excluding Norway maple (*Acer platanoides*)), baldcypress (*Taxodium*), catalpa (*Catalpa*), planetree (*Platanus*), and dawn redwood (*Metasequoia*) comprise the taxa that are of interest but that are not currently dominant campus trees. Unlike the list of "important" species, which were relatively consistent in magnitude of tree frequency, the number of trees within each genus of interest varies from 13 to 476 (all counts shown in Table 13 in Appendix C). Thus, age and condition class breakdowns of these genera are best visualized in a different way than for the "important" species. To ensure readability of figures, stacked bar charts were chosen over mosaic plots so that only the age/condition class variables, rather than both age/condition class and genus, are represented dimensionally.

Overall, individuals in taxa of interest to FS are predominantly in the "young" age class, except for catalpa (*Catalpa*) and linden (*Tilia*). Since lindens (*Tilia*) are also on the list of "important" trees, planning for their impending replacement should take higher priority than planning for the replacement of catalpa (*Catalpa*) trees, of which there are only 25. Since the number of trees on campus within each genus of interest varies highly, tree frequencies may be more helpful than age class distributions when deciding which genus to plant (as in the previous catalpa (*Catalpa*) example). Planting more trees of the genera that do not currently have a large presence will increase their IV in the campus forest in coming decades.

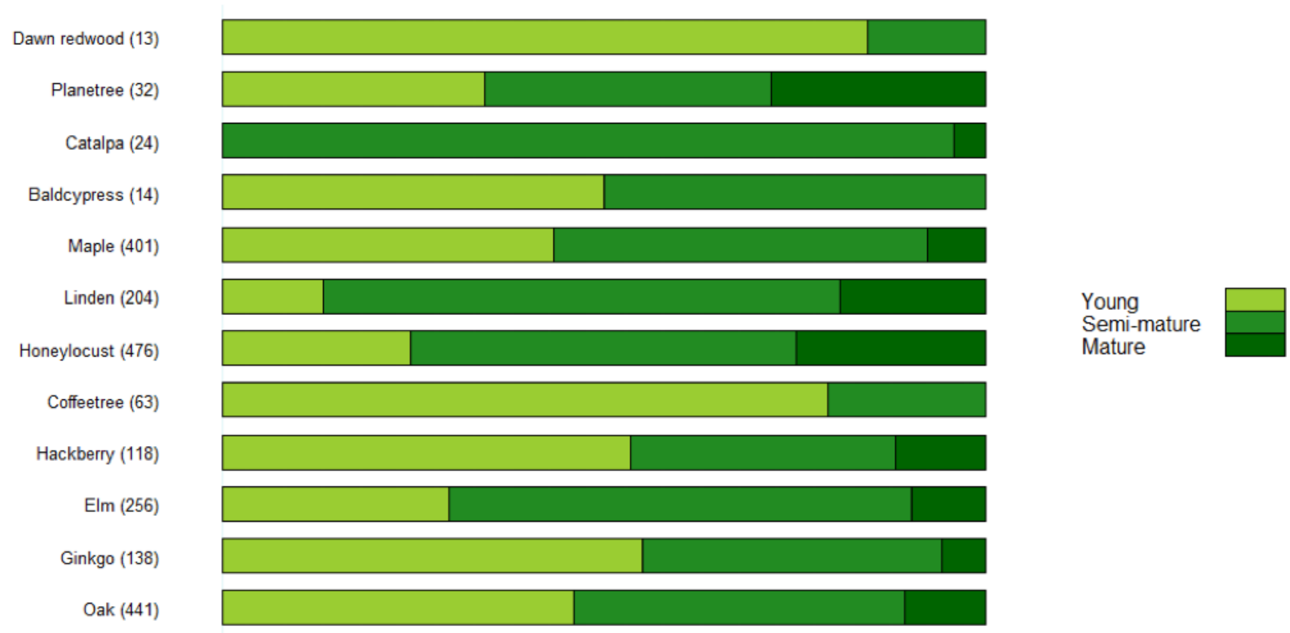

Figure 8: Genera of Interest by Age Class. *New planting and over-mature categories are omitted (10 trees) because they contain few trees and would not be easily readable in the figure. Oak includes swamp white (Quercus bicolor), bur (Quercus macrocarpa), northern red (Quercus rubra), English (Quercus robur), shingle (Quercus imbricaria), chinkapin (Quercus muehlenbergii), black (Quercus velutina), white (Quercus alba), swamp chestnut (Quercus michauxii), pin (Quercus palustris), and sawtooth oak (Quercus acutissima). Elm includes elm spp (hybrid cultivars), American (Ulmus americana), Siberian (Ulmus pumila), and slippery elm (Ulmus rubra). Hackberry includes hackberry (Celtis occidentalis) and southern hackberry (Celtis laevigata). Coffeetree includes Kentucky coffeetree (Gymnocladus dioicus). Honeylocust includes thornless common (Gleditsia triacanthos var. inermis) and common (Gleditsia triacanthos). Linden includes littleleaf (Tilia cordata), American (Tilia americana), and silver (Tilia tomentosa). Maple includes freeman (Acer freemanii), red (Acer rubrum), sugar (Acer saccharum), silver (Acer saccharinum), hedge (Acer campestre), paperbark (Acer griseum), Amur (Acer ginnala), boxelder (Acer negundo), and Japanese (Acer palmatum). Baldcypress includes common baldcypress (Taxodium distichum). Catalpa includes northern catalpa (Catalpa speciosa). Planetree includes London planetree (Platanus x acerifolia) and American sycamore (Platanus occidentalis). See Table 14: Genera of Interest by Age Class for bar values and Table 13: Campus Frequency of Genera of Interest in the Appendix for counts of each genus on campus. Bar heights are not proportional to the number of trees in each genus, but bar widths are proportional to the number of trees within a variable category assessed across a genus. The tree frequency of each genus (excludes trees in omitted variable categories) is listed next to its name.*

Among the tree genera of interest to FS, good and fair conditioned trees are prevalent, similar to with the most "important" trees. While the planetree genus (*Platanus)* has the smallest proportion of good condition trees, planetrees (*Platanus*) number only 32 on campus, so they do not pose a significant risk to forest health if removed. The lower general health of planetrees (*Platanus*) may be due to susceptibility to anthracnose (*Glomerella cingulata*), though the cause of a particular species' or genus's poor health is often difficult to pin down. Contributing factors can include stress from warming temperatures, precipitation changes, extreme weather events, and pest and disease outbreaks, which are all projected to worsen over the course of the century.

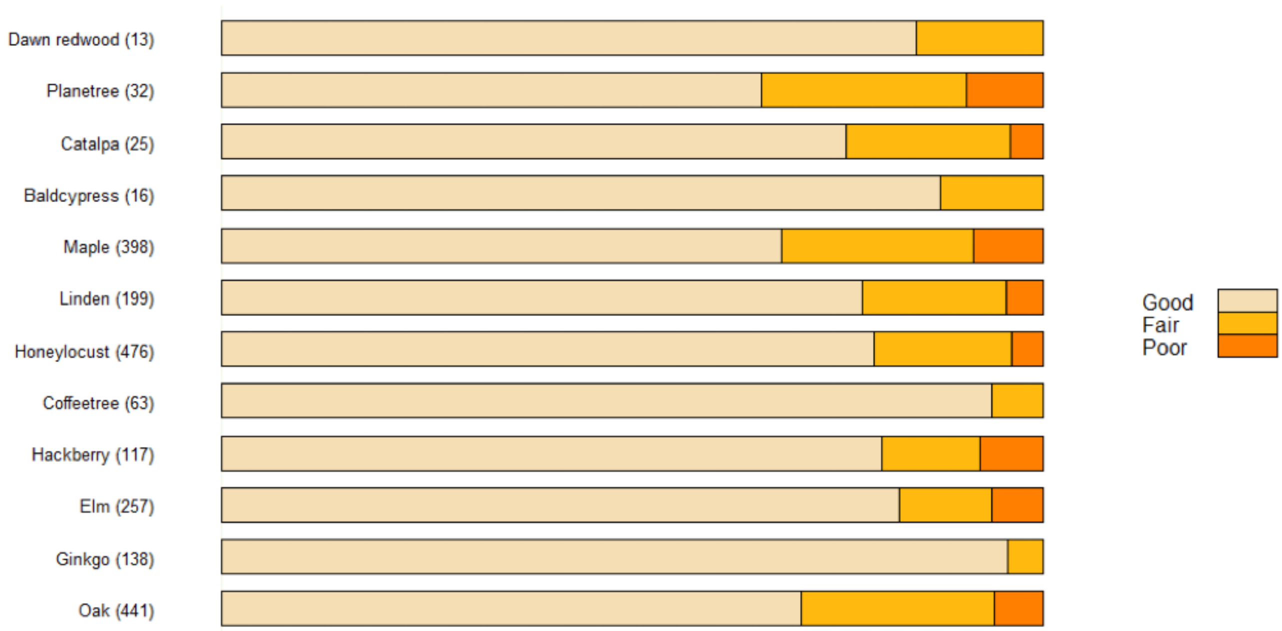

Figure 9: Genera of Interest by Condition Class. *Dead category is omitted (15 trees) because it contains few trees and would not be easily readable in the figure. Oak includes swamp white (Quercus bicolor), bur (Quercus macrocarpa), northern red (Quercus rubra), English (Quercus robur), shingle (Quercus imbricaria), chinkapin (Quercus muehlenbergii), black (Quercus velutina), white (Quercus alba), swamp chestnut (Quercus michauxii), pin (Quercus palustris), and sawtooth oak (Quercus acutissima). Elm includes elm spp (hybrid cultivars), American (Ulmus americana), Siberian (Ulmus pumila), and slippery elm (Ulmus rubra). Hackberry includes hackberry (Celtis occidentalis) and southern hackberry (Celtis laevigata). Coffeetree includes Kentucky coffeetree (Gymnocladus dioicus). Honeylocust includes thornless common (Gleditsia triacanthos var. inermis) and common (Gleditsia triacanthos). Linden includes littleleaf (Tilia cordata), American (Tilia americana), and silver (Tilia tomentosa). Maple includes freeman (Acer freemanii), red (Acer rubrum), sugar (Acer saccharum), silver (Acer saccharinum), hedge (Acer campestre), paperbark (Acer griseum), Amur (Acer ginnala), boxelder (Acer negundo), and Japanese (Acer palmatum). Baldcypress includes common baldcypress (Taxodium distichum). Catalpa includes northern catalpa (Catalpa speciosa). Planetree includes London planetree (Platanus x acerifolia) and American sycamore (Platanus occidentalis). See Table 15: Genera of Interest by Condition Class for bar values and Table 13: Campus Frequency of Genera of Interest in the Appendix for counts of each genus on campus. Bar heights are not proportional to the number of trees in each genus, but bar widths are proportional to the number of trees within a variable category assessed across a genus. The tree frequency of each genus (excludes trees in omitted variable categories) is listed next to its name.*

3.4.3 Vulnerable Species Spatial Distribution

The campus forest's current health and climate change vulnerability can be modeled in ways beyond age and condition. Mapping vulnerable trees provides a visualization of where the campus forest may suffer in the future, and thus where new plantings should occur. Table 5 displays projected responses of the most "important" tree species on campus (i-Tree metric) and the species of interest to FS to climate change. The relative quantity and canopy size of "important" species indicates that they contribute significantly to the structure and function of the campus forest; potential threats to "important" species health must be considered and mitigated by succession planning. Most "important" species are projected to fare moderately well or well by all measures in Table 5, with the exception of the predicted Heat/Hardiness Zone Effect for green ash (*Fraxinus pennsylvanica*) trees. Green ash (*Fraxinus pennsylvanica*) trees are additionally impacted by the Emerald Ash Borer (*Agrilus planipennis*), which decimated 6 million of Chicago's ash trees in the past decade (The Morton Arboretum, 2021). Trees planted by the city of Chicago, such as along Cottage Grove Ave, 59th St, and 55th St, are not inoculated against the pest (in contrast to University trees that *are* inoculated), and should accordingly be monitored for any outbreaks (Representative of Facilities Services, personal communication, July 29, 2021). For these reasons, we map green ash (*Fraxinus pennsylvanica*) trees in Figure 10 to show potential spatial vulnerabilities in the UChicago campus forest.

Three tree species within the FS interest list fall in the lowest ranking in one or more climate projection categories in Table 5 and are also represented in Figure 10. The American linden's (*Tilia americana*) Capability Ranking is "very poor," the Amur maple's (*Acer ginnala*) Climate Change Vulnerability is "moderate-high" and its effects of Heat/Hardiness Zone changes are negative, and the northern catalpa (*Catalpa speciosa*) ranks "moderate-high" in Climate Change Vulnerability and is "low" in Planted Adapt Class. Figure 10 shows the locations of these at-risk trees on campus, as well as the locations of green ash (*Fraxinus pennsylvanica*) trees (the at-risk species from i-Tree's IV rankings), according to the UChicago 2020 Tree Inventory. Though the American linden (*Tilia americana)*, Amur maple (*Acer ginnala*), and northern catalpa (*Catalpa speciosa*) each make up a small fraction of the total campus forest (only 2% altogether), American lindens *(Tilia americana*) dominate along University Ave north of the main quadrangle and northern catalpas (*Catalpa speciosa*) dominate the green space south of the Campus North parking garage. Green ash (*Fraxinus pennsylvanica*) trees are grouped tightly along streets throughout campus. The predicted climate risk to all four at-risk tree species may cause loss of local tree ES in these areas. Alternative tree species should be planted in the areas populated by these trees to decrease the IV of green ash (*Fraxinus pennsylvanica*) trees, supplement local ES, and prepare for a robust future forest in the face of climate change.

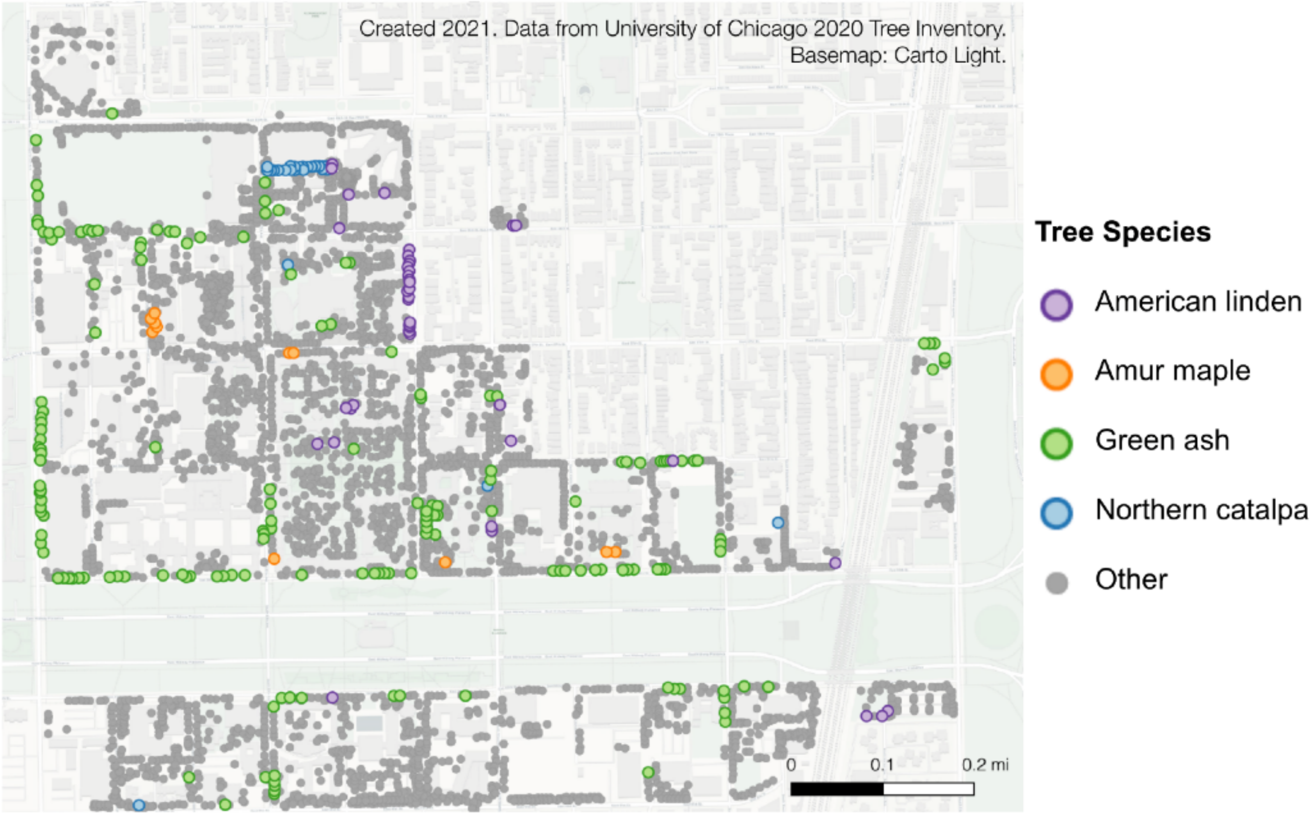

Figure 10: Spatial Distribution of At-Risk Tree Species. *The map includes species of interest to FS – American linden (Tilia americana), Amur maple (Acer ginnala), and northern catalpa (Catalpa speciosa) – predicted to do unfavorably in Chicago's changing climate according to metrics included in Table 5. Green ash (Fraxinus pennsylvanica) trees are included due to similarly unfavorable predictions in Table 5 and their top-ten IV ranking according to the 2020 i-Tree Ecosystem Analysis. The "Other" trees category includes all other trees on campus.*

3.4.4 "Important" Species Spatial Distribution

The increasing vulnerability of urban trees to pests and diseases (discussed in Section 2.3.3: Pests and Disease) poses additional challenges to the campus forest. The high quantity of "important" tree species makes them particularly vulnerable to rapidly spreading pests and pathogens; the resulting damage could be extensive due to the large leaf area these trees provide. Figure 11 shows the distribution of the 10 most "important" UChicago tree species, with the legend noting susceptibility to pests found in Cook County according to the 2020 i-Tree Report. The University has 129 total species of trees on campus; 10 are highlighted on this map and the remaining 119 species are not shown. Excluded species likely dominate many areas that appear grey on the map. Figure 11 demonstrates that many "important" species appear in groupings; however, trees with low IV also exist in these groupings but are not shown on the map. Some species, like common honeylocusts (*Gleditsia triacanthos*) and ginkgos (*Ginkgo biloba*), mainly line streets like Ellis Ave. Other species, like bur (*Quercus macrocarpa*) and swamp white oaks (*Quercus bicolor*), are evidently grouped on lawn spaces like the main quadrangle. Such a map provides a visualization of the campus tree landscape for FS and non-FS members to note areas of species clustering and potential climate or pest vulnerabilities. In spaces on campus where vulnerable species dominate, the University must diligently monitor and respond to pest and disease presence. However, some genera include cultivars hybridized for resistance to pests; younger campus elms (*Ulmus spp*) are resistant to Dutch Elm

Disease and can continue to be planted, for example. The University should consider lessening the IV of individual at-risk trees by planting different species (therefore increasing diversity), in turn preventing future pest and pathogen damage.

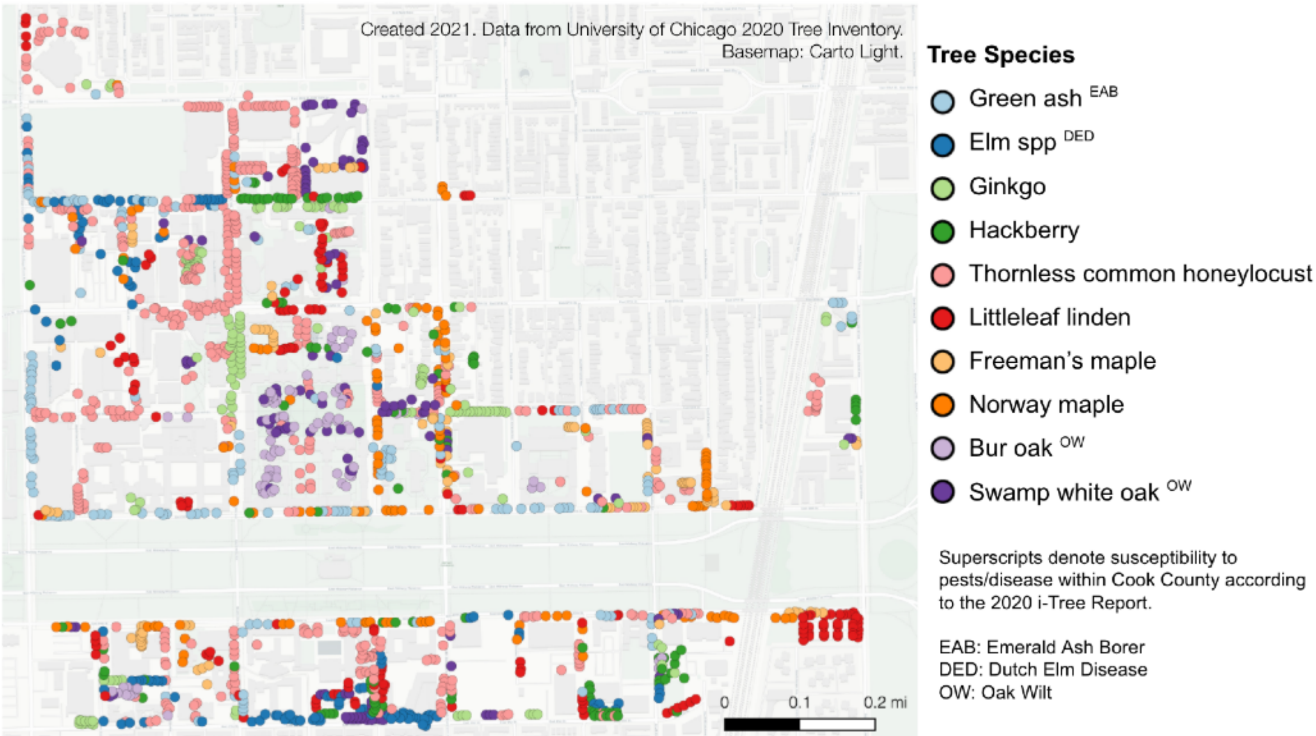

Figure 11: Spatial Distribution of Campus "Important" Species. *The species included were selected based on their top-ten Importance Value (IV) rankings according to the 2020 i-Tree Ecosystem Analysis. A species' IV is the sum of its percent of total population and its percent of total tree leaf area the species comprises on campus. The trees represented in this map comprise 43.4% of total trees and 53.3% of total tree leaf area on campus.*

3.5 Current Considerations in Tree Planting

Facilities Services at the University of Chicago selects new trees for planting based on a variety of key factors. Such considerations aim to ensure that selected trees will be well-matched to their environment and boast long life spans. The current planting considerations are detailed below and visualized in Figure 12, as informed by a representative of FS (personal communication, July 29, 2021).

<u>Funding</u>

All tree-related procedures must fit within the financial constraints of annual FS budget allocations. The current budgeting allows for the planting of 16 to 20 new trees (not including trees associated with new construction) each year.

Site Focus

To increase the long-term success of newly planted trees, attention must be paid to numerous site conditions.

- Biodiversity is prioritized to enhance the ecological connectivity of the campus forest and to prevent widespread pest and disease outbreaks (Jackson, 2014; University of California, Riverside, 2012).

- Priority is given to replacing removed trees so the campus forest can maintain or increase its number and spatial distribution of trees.

- Placement of trees at the appropriate distance from buildings and structures is necessary to allow for full canopy growth, especially with larger species ("Factors to Consider," n.d.). Gilman (1994, as cited in Community-Planning-Zoning, 2019) recommends that large trees be planted 15 or more feet from buildings, while small and medium trees may be planted closer with regular pruning. The University of California, Riverside (2012) recommends a distance of 15 feet from lamps, 10 feet from light poles and tall structures, and 5 feet from fire hydrants and small structures.

- Matching tree species to Chicago's sandy soils and site conditions of soil pH, texture, moisture, drainage, and compaction is essential to provide trees with proper nutrient and hydration levels (Hughes et al., 2015; Community-Planting-Zoning, 2019; "Factors to Consider," n.d.; Jackson, 2014; Urban Horticulture Institute, 2009).

- Not all tree species thrive equally in constrained or open areas; selection of trees is based on their ability to grow beside buildings and roadways (parkway trees) or in open spaces (lawn trees) (Community-Planting-Zoning, 2019; "Factors to Consider," n.d.).

- The need for sun and sensitivity to wind and shade exposure are species-specific and are considered during selection to reduce stress and limit premature mortality (Hughes et al., 2015; "Factors to Consider," n.d.; Jackson, 2014; Urban Horticulture Institute, 2009). The New York City Department of Parks & Recreation (2013) recommends acknowledging the potential responses of trees to changes in light conditions over time (for instance, when a new building is constructed that blocks sunlight).

- The University has an extensive network of underground water, waste, heating, and other systems that are avoided to allow for full root growth (Urban Horticulture Institute, 2009). Trees should be planted a distance of 12 or more feet from major underground utility lines, recommends Gilman (1994, as cited in Community-Planning-Zoning, 2019).

- Current and projected University construction plans are taken into account when selecting planting sites so as not to remove newly planted trees (Community-Planning-Zoning, 2019; "Factors to Consider," n.d.; Urban Horticulture Institute, 2009).

- Finally, pest and disease threats are assessed before planting tree species that may be at risk so as to decrease the risk of outbreaks and widespread forest damage.

Situational Focus

A limited number of tree ecosystem services are implicitly considered in University planting selections once conditions for tree survival have been ensured. Incorporating such tree provisions sets the stage for an expanded consideration of ecosystem services.

- Provision of shade is taken into account, both positively (near buildings and pedestrian walkways) and negatively (blocking sun from other trees).

- Trees are also used on campus to obscure the human line of sight (e.g., when blocking building mechanicals).

Aesthetic Focus

The visual appeal of trees is also a factor in planting selections, though one that does not surpass site and situational focus in priority.

- The mature shape and form of a tree must be aesthetically pleasing and visually harmonious with surrounding trees.

- A tree's flowering or fruit-bearing ability is accounted for, especially to prevent inopportune droppings or unwanted animal attraction.

- In dioecious trees, sex is considered because it impacts tree characteristics (e.g., messy fruit with potent odor) and form (i.e., tree shape or color). However, some nurseries clone trees to ensure only one sex is planted (e.g., male ginkgos)

New design, existing landscape, precedents

The University of Chicago has a distinctive design and aesthetic. New plantings generally align with the existing landscape to ensure a visually complementary campus. Alternatively, trees can be used to achieve new design visions, as seen throughout the University's history.

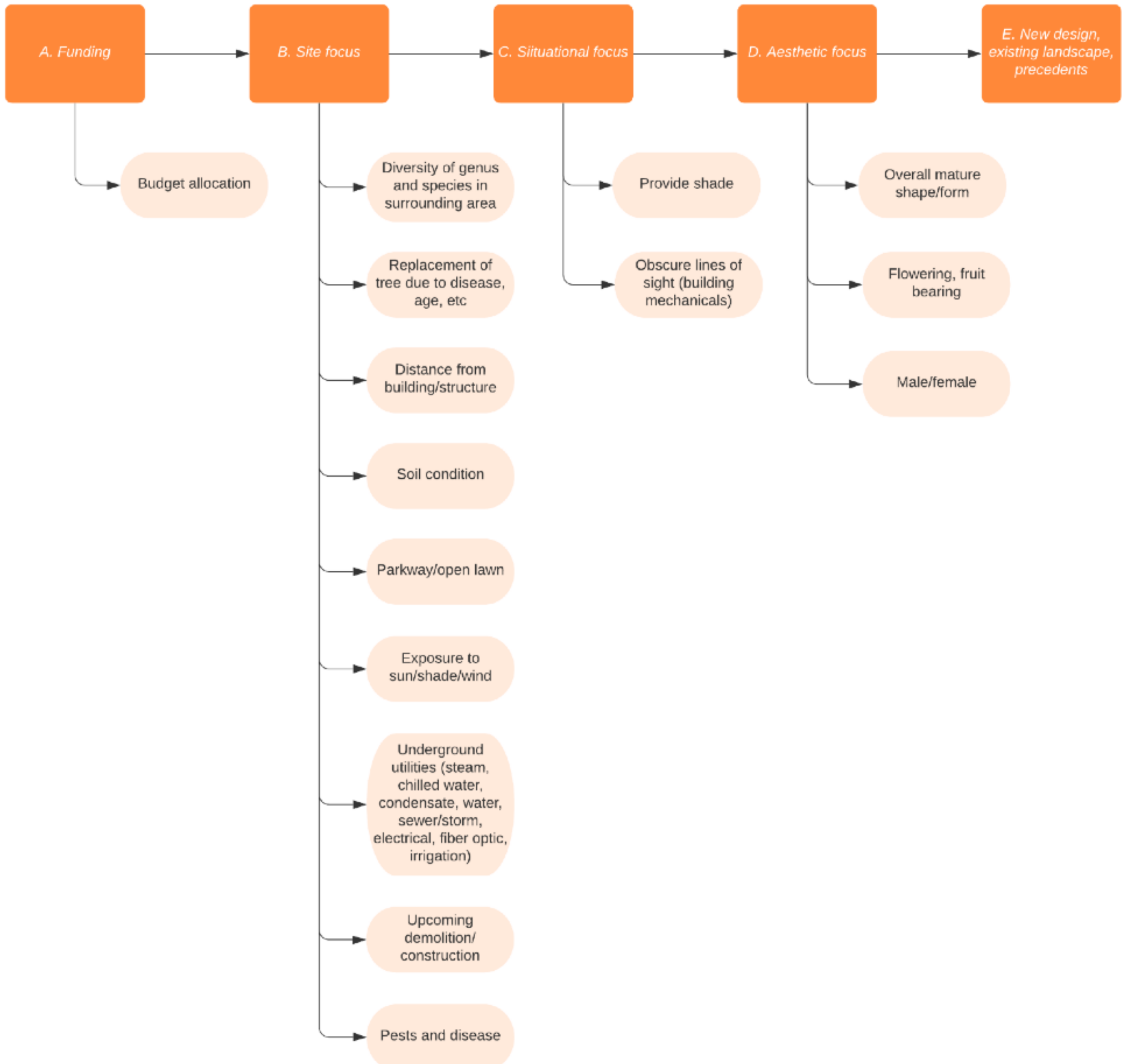

Figure 12: Current Tree Consideration Process at the University of Chicago. *The lettered dark orange boxes follow the current FS order of considerations. All bubbles of the same color are of equal priority except for the topmost, lettered boxes.*

3.6 Recommended Considerations in Tree Planting

Based on extensive research and quantification of University tree ecosystem services and climate change projections, as summarized in Sections 1: Ecosystem Services, 2: Climate Change, and the Appendices, we suggest the addition of both to current FS tree planting considerations. Figure 13 displays our recommended process of tree selection for FS at the University of Chicago. The categories of considerations, in order of priority, include funding (i.e., budget allocations), site focus (i.e., ensuring tree survival), situational focus (i.e., benefitting human wellbeing), and aesthetic focus, which subsumed the current process's 5th section (i.e., creating a visually appealing campus). We propose the addition of ES to situational focus considerations due to the numerous benefits that trees provide to the campus community, which are implications of tree presence rather than logistical planting matters. Explicitly selecting species and sites based on maximization of these benefits, and on minimization of ecosystem disservices, will bolster the functional value of the campus forest. We propose the addition of climate change to site focus considerations due to the rapidly changing, location-dependent environmental conditions slated to affect trees on short- and long-term scales (New York City Department of Parks & Recreation, 2013). Selecting species that are both extreme weather-tolerant and predicted to survive in future Chicago hardiness zones will allow for extended tree lifespans and reduced energy and financial costs associated with premature tree removal (Hughes et al., 2015; Urban Horticulture Institute, 2009).

Since ES provision is predicted to alter with climate change, it should be continually assessed in i-Tree reports and accordingly capitalized on in tree management decisions. General relativization of ES should also be incorporated in management decisions. For example, carbon storage/sequestration is not an impactful ES on campus due to its small scale compared to University emissions, and is predicted to decrease in provision long-term with drought and extreme weather stress; trees should not be planted based primarily on their carbon sequestration abilities, but rather based on numerous other, more impactful ES. The recommended tree consideration process flowchart should serve as a guide that incorporates all necessary considerations for succession planning decisions regarding forest resilience and benefit provision. Adoption of this flowchart is a crucial first step in making robust forest management decisions.

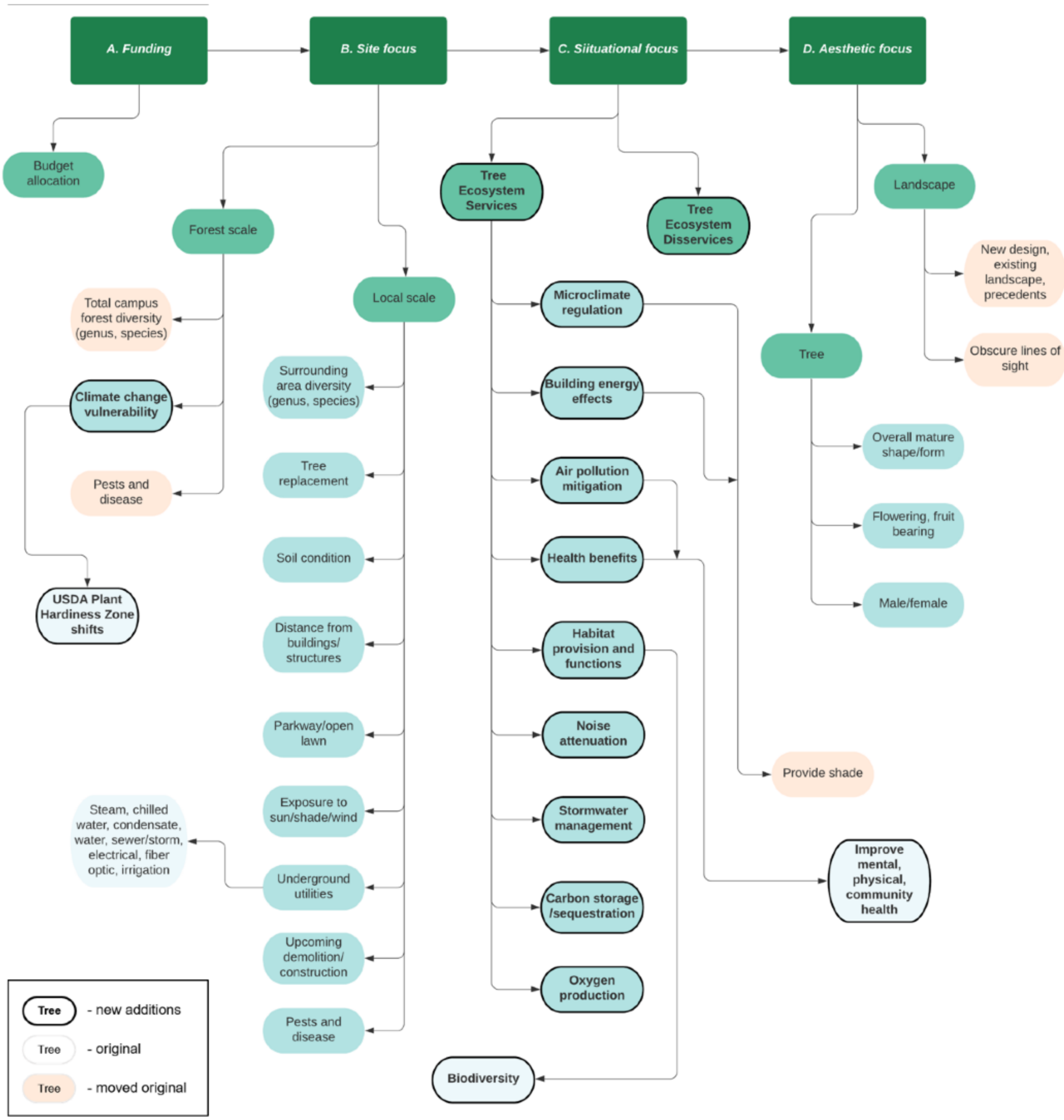

***Figure 13: Recommended Tree Consideration Process at the University of Chicago**. The lettered dark green boxes follow the current FS order of considerations. Each subsequently lighter color indicates a new level of consideration. All bubbles of the same color are of equal priority except for the topmost, lettered boxes. Bolded and outlined bubbles indicate new additions to planning considerations. Light orange bubbles indicate information that was previously considered by FS but that has been reorganized in the recommended process.*

3.6.1 Future Species for Planting

Extensive research by Facilities Services informs selecting a new tree for planting. Climate change is a new, significant consideration in tree selection added in the recommended flowchart (see Figure 13). To streamline and shorten the process of tree selection, we present a variety of tree species with the best climate change rankings (as shown in Table 5 in Section 2.4.1: Effects on UChicago Trees) below in Table 6. The table includes species present in high and low quantities on UChicago's campus, as well as species not yet planted on campus. The columns detail characteristics of each species that are helpful in site selection, like ideal light and soil conditions and tolerance to different environmental stressors. The aim of this table is to provide FS with an easily accessible and readable list of species to plant on campus that can be cross-checked against campus site conditions to ensure long-lived trees. We recommend that Table 6 be consulted during Section B. of the selection process, site focus, in conjunction with climate change vulnerability considerations.

Each included tree species has its own physiological and phenological characteristics that should additionally be taken into consideration during the selection process. Hedge maples (*Acer campestre*), for example, have invasive traits that the Morton Arboretum cautions against (The Morton Arboretum, 2021). Some species are explicitly recommended to replace ash trees (after mortality from the EAB) in size and beauty, like miyabe maples (*Acer miyabei*). Other trees (e.g., Pacific Sunset® maples (*Acer 'warrenred'*), elm hybrid cultivars like the Accolade® elm (*Ulmus ACCOLADE*™)) are specifically bred to withstand pests and urban conditions and should be increased in number on campus to foster forest resilience to these challenges. Some genera, like cherry trees (*Prunus)* and junipers (*Juniperus*), are sparsely planted on campus and could thus be used to diversify the forest if planted, adding visual appeal and ecological stimuli. Many species in the table are nonnative, though none are invasive species or at high risk for pest or disease outbreaks.

Additionally, many of the species in the table are tolerant of drought, air pollution, and salt. Due to UChicago's urban setting, these species are especially recommended. Most of the trees are suited to both parkway and lawn conditions, so more fine-scale site aspects (soil pH, hours of shade, etc.) can be assessed sooner in the site selection process. We also recommend planting of species which currently have low presence on campus (<10 trees) to increase campus biodiversity and beauty.

Family, Genus Botanical Name	Species Common Name	Hard-iness Zones	Heat Zones	Light Conditions	Soil Conditions and pH	Drought Tolerant	Air Pollution Tolerant	Salt Tolerant	Park-way vs. Open Lawn
Cannabaceae, Celtis	hackberry, northern (117)	3-9	9-1	Full sun, part shade	Rich, moist, pH 8.2	Yes	Yes	Yes	Both
Cupressaceae, Juniperus	juniper, Chinese (0)	4-9		Full sun, part shade	Moist, well-drained pH 8.0	Yes	Yes	Yes	Both
Cupressaceae, Taxodium	baldcypress, common (16)	4-11	12-5	Full sun, part shade	Moist, well-drained, pH 7.5	No	No	Yes	Both
Fabaceae, Gymnocladus	coffeetree, Kentucky (63)	3b/4-8	9-2	Full sun	Adaptable, pH 8.2	Yes	Yes	Yes	Both
Fagaceae, Quercus	oak, bur (93)	3-8	9-1	Full sun	Adaptable, pH 8.2	Yes	Yes	Yes	Both
Fagaceae, Quercus	oak, chestnut (0)	4-8		Full sun	Well-drained, pH 8.2	Yes		Yes	Both
Fagaceae, Quercus	oak, Heritage® (0)	4-8		Full sun	Well-drained, pH 8.2	Yes	Yes	Yes	Open Lawn
Fagaceae, Quercus	oak, willow (0)	5-9	9-3	Full sun	Adaptable, pH 7.5	No	Yes	Yes	Both
Ginkgoaceae,Ginkgo	Ginkgo (138)	4-8	9-3	Full sun	Adaptable, pH 8.2	Yes	Yes	Yes	Both
Malvaceae, Hibiscus	Rose-of-Sharon (0)	5-9		Full sun, part shade	Moist, well-drained, pH 7.5	Yes	Yes	Yes	Both
Malvaceae, Tilia	linden, littleleaf (162)	3b-8	8-1	Full sun, part shade	Deep, moist, fertile, pH 8.2	No	Yes	Yes	Both
Oleaceae, Chionanthus	fringetree, Chinese (0)	6-8	9-3	Full sun, part shade	Adaptable, well-drained, pH 7.5	Yes	Yes	No	Both
Oleaceae, Chionanthus	fringetree, white (0)	4-9	9-1	Full sun, part shade	Deep, moist	No	Yes	Yes	Open Lawn
Rosaceae, Prunus	cherry, Amur (0)	3-7		Full sun, part shade	Moist, well-drained, pH 7.5	Yes	Yes	Yes	Both
Sapindaceae, Acer	maple, freeman (103)	4-8		Full sun	Adaptable, pH 7.5	No	Yes	Yes	Both
Sapindaceae, Acer	maple, hedge (41)	5-8		Full sun	Adaptable, pH 8.2	Yes	Yes	Yes	Both
Sapindaceae, Acer	maple, miyabe (0)	4-8		Full sun, part shade	Moist, well-drained, pH 8.2	Yes	Yes	Yes	Both

Sapindaceae, Acer	maple, Pacific Sunset® 🌲 (0)	4b-		Full sun	Well-drained, pH 8.2	Yes	Yes	Yes	Both
Sapindaceae, Acer	maple, shantung 🌲 (0)	5-		Full sun	Well-drained, pH 8.2	Yes	Yes	Yes	Both
Ulmaceae, Ulmus	Elm, hybrid cultivars 🌲 (~127)	4-9		Full sun, part shade	Adaptable, pH 8.2	Yes	Yes	Yes	Both
Ulmaceae, Zelkova	zelkova, Japanese (0)	5-8	9-5	Full sun	Moist, deep, pH 8.2	No	Yes	Yes	Both

🌳Top 10 i-Tree "Important" Species
🌲 Genus of interest to FS
No trees currently on campus
Discrepancy between sources
Insufficient information

Table 6: Characteristics of Trees Projected to Succeed in Chicago's Future Climate. *The frequency of each species in the table is listed next to the species common name and is based explicitly on Bartlett's 2020 UChicago Inventory. Only species with hardiness zone ranges that encompass Chicago's current and projected zones are included.*

(Arbor Day Foundation, n.d.; Arbor Valley, 2021; Backyard Gardener, n.d.; Battersby, 2013; Chicago Botanic Garden, n.d.; Chicagoland Grows, n.d.; City of Sioux Falls, n.d.; Donovan Arborists, 2016; Fazio, 2020; Gilman and Watson, 1994; Hughes et al., 2015; J. Frank Schmidt & Son Co., n.d.; Klyn Nurseries Inc., n.d.; Loughrey, n.d.; Mahr, n.d.; McKay Nursery Co., n.d.; Michigan State University Extension, n.d.; Millcreek Gardens, 2019; Millcreek Nursery Ltd, n.d.; Missouri Botanical Garden, n.d.; Nature Hills Nursery, Inc., n.d.; NC Cooperative Extension, n.d.; North Dakota State University, n.d.; Oakland Nurseries, n.d.; Ohio Department of Natural Resources, n.d.; Russ, 2010; Society of Municipal Arborists, 2017; Southern Oregon University Landscaping, 2019; The Morton Arboretum, 2021; University of Kentucky Department of Horticulture, n.d.; University of Minnesota Extension, n.d.; Urban Horticulture Institute, 2009)

3.7 Synthesized Recommendations for University Succession Planning

Below we present a consolidated list of tree maintenance and planting recommendations for Facilities Services at the University of Chicago. Extensive research and acknowledgement of University capabilities inform these synthesized recommendations. The recommendations are listed in order of priority, though all contribute to managing a resilient and service-providing forest. Recommendations 1, 3, 4, and 8 involve altering the selection process for tree plantings on campus to prioritize ecosystem services, climate resilience, and overall forest health. Recommendations 2, 5, and 6 concern prioritizing current tree health by monitoring the forest for site fitness and tree longevity. Recommendations 7 and 10 relate to University energy expenditure and how to incorporate trees and forest maintenance in reducing carbon outputs. Recommendation 9 refers to further data collection for increased quantification of ES benefits, as suggested in Section 4: Future Directions. We advise adoption of Recommendation 1 first, since later recommendations will naturally follow as the updated selection process is carried out. Following Recommendation 1, these recommendations can be implemented in any order because they are independent from one another. Once adopted, the recommendations will improve the structural and functional value of the campus forest, as well as the sustainability of the University.

Succession Planning Recommendations

1. Adoption of the updated flowchart for the tree planting process (Figure 13). This will ensure that forest climate change vulnerability and ecosystem services provision are accounted for in tree and site selection, thereby promoting ecosystem-based adaptation. (Sections 3.2, 3.6)

2. Further attribution of equal or greater significance to maintaining campus trees as to planting new trees. Fostering a healthy forest with low tree mortality rates will decrease carbon emissions and financial expenditures, as well as sustain ES. (Sections 3.4.1, Appendix A.1)

3. Explicit prioritization of biodiversity (ages, species, phenotypes, physiologies) at the species and forest scale. Areas of same-species groupings, as shown in Figure 11, should be addressed in site selections first, followed by areas of low diversity. Diversity establishes forest resiliency, a crucial component of ecosystem-based adaptation, and fosters both a more complex ecological system and a more visually appealing landscape. (Sections 1.3.2, 2.4.1, 3.2, 3.4.3, 3.5, 3.6.1, Appendix A.1, Appendix A.6, Appendix A.7, Appendix A.9)

4. Planting only tree species with plant hardiness zone ranges that include Chicago's current zones (5b-6a) and projected zones to 2099 (6a-7b) (as depicted in Table 4). Selecting species adapted to Chicago's present and future winter temperatures will decrease the likelihood of tree failure. (Sections 2.3.2, 2.4.1, 3.6)

5. Heightened assessment and amelioration of soil condition (nutrient levels, compaction, water content, etc.) prior to and after planting a tree. Poor soil quality is one of the primary causes of urban tree death and should remain a primary site consideration. (Sections 2.3.1, 2.4.1, 2.4.2, 3.5, 3.6.1, Appendix B.1, Appendix B.2)

6. Continued pest and disease monitoring (Emerald Ash Borer (*Agrilus planipennis*), Dutch Elm Disease, Oak Wilt, etc.) and avoided planting of pest-susceptible species (like some ashes (*Fraxinus*) and oaks (*Quercus*)). To prevent widespread tree infection and mortality, at-risk species should continue to be identified and not planted in clusters, although hybridized cultivars of such species can be favored. (Sections 2.3.3, 2.4.1, 2.4.3, 3.4.2, 3.4.3, 3.4.4, 3.5, 3.6.1, Appendix B.2)

7. Use of lower-energy tree planting and maintenance practices (handsaws and rakes instead of chainsaws and leaf blowers) when feasible. Such practices help prevent reaching the LPP (Last Positive Point), and thus allow individual trees to act as carbon sinks rather than carbon sources, improving the University's carbon footprint (Sections 2.4.1, 2.4.2, 3.4.2, Appendix A.1, Appendix B.1)

8. Incorporation of trees' ability to improve individual and community health (mental and physical) in site and species selections. Improved health is one of the primary services UChicago's campus trees provide to the community and is projected to become more impactful with climate change. (Sections 1.2, 1.3.2, 2.3.1, 2.4.2, Appendix A.8, Appendix B.3)

9. Collection of building energy, tree canopy area, human behavioral/psychological, and biodiversity data to assess more tree ES (building energy effects, human health benefits, habitat provisions and functions, etc.). Understanding how campus trees affect building energy expenditure, individual and community health, and ecological systems is a crucial next step in maximizing ES benefits and reducing campus carbon emissions. See Future Directions (Section 4) for more information. (Sections 1.5, 3.6, 4)

10. Recognition that campus forest carbon storage/sequestration is not a viable solution to University carbon emissions reduction. University Sustainability Plans should not rely on campus trees as a major source of carbon storage (0.459% University emissions) or sequestration (0.0088% University emissions) (Section 1.3.3), and FS cannot feasibly plant 1.28 million more hardwood trees to heighten this ES. Rather, other benefits that trees provide should be emphasized in sustainability planning. (Sections 1.3.1, 1.3.3, 2.3.1, 2.4.2, Appendix A.1, Appendix B.1)

3.8 Conclusion

The University of Chicago's campus forest is dynamic and indispensable. Facilities Services' support of the forest's current needs and prioritization of its future success will help ensure high functional and structural forest valuation. Due to the significant contribution of tree ecosystem services to the campus and surrounding communities, we propose that ecosystem services be prioritized in succession planning. Adopting ES and their potential changes with time and climate as part of tree planning situational focuses (Figure 13) will help maximize the unique benefits of the campus forest now and in the future. Additionally, climate change poses a challenge to global biodiversity while also being felt at the local (Chicago) and community (UChicago) levels. Incorporating Chicago and Illinois climate projections into tree planning site focuses (Figure 13) significantly contributes to guaranteeing long-lived campus trees. Generally, increasing diversity (age, species, size, etc.) of the campus forest will confer greater resistance to pest/disease outbreaks, extreme weather detriment, and homogenous aesthetics. Based on data from the UChicago 2020 Tree Inventory and i-Tree Ecosystem Analysis, UChicago's trees are not at significant risk to climate change or pest outbreaks. There is an abundance of trees of the same species in many areas, however, and increasing biodiversity should be prioritized in these locations. Though generally planting more trees on campus is recommended, proper selection of trees for current and future site conditions is paramount. Maintenance of current trees is no less significant; success of trees should be favored over objective numbers of trees to save money and lower carbon emissions spent in tree replacement. Evidence-based and continually updated tree management practices will help the University care for its current trees and thoughtfully select future ones, thereby strengthening the environmental and human benefits and improving the resiliency of our urban campus forest.

4. Future Directions

This report and the 2020 UChicago i-Tree Ecosystem Analysis provide the groundwork for future assessments of the University of Chicago campus forest. Suggestions from EFCampus stakeholders and other faculty of the University, as well as our own interests and ideas, inform the following proposed research directions.

Human/Psychological

Trees provide numerous mental and physical health benefits that are impactful on UChicago's campus. Quantifying these benefits would give a better picture of a key ecosystem service that is expected to increase in impactfulness on campus with climate change. Individual students, faculty, and community members could contribute to data collection by reporting their own observed improvements in health when around campus trees, perhaps through a phone app, online reporting system, survey, or interview. Initial research could center on one location, like the main quadrangle, for ease of study. Professor Mark Berman's research on noise could also be incorporated in this research direction; early development of an app that assesses location quality based partly on noise levels is underway. Students, faculty, and community members could test this app or an alternative program to report data on noisiness, scenic quality, and mood in various campus locations with trees. The Midway could be an initial research location, as it is already identified as the noisiest location "on" campus. A list or graphic of the most scenically desirable and calming study locations on campus could be one deliverable from this research avenue. Explicitly exploring the ties between trees and human psychology would provide further justification for the significance of trees on UChicago's campus, contribute to a young area of psychological research, and potentially improve the campus experience for its inhabitants.

Energy/Systems

An existing focus of EFCampus is assessing campus building energy consumption. Trees could be integrated into this research focus through studying the ecosystem service of building energy effects. Since trees' main influences on buildings is shading, collection of tree canopy area data through satellite imagery, drone footage, and/or on-the-ground measurements, as well as gathering of building energy use data (air conditioning and heating hours, expense reports, etc.) would be crucial first steps. i-Tree Eco Software could be used to conduct the initial building energy effects analysis, since it has these capabilities when the necessary data are inputted (the necessary data were not collected during Bartlett's UChicago 2020 Tree Inventory, so this analysis was not produced for the 2020 i-Tree Ecosystem Analysis). Later analyses may focus on seasonal differences in the building energy effects of trees and how knowledge of their dynamics on campus could be implemented in tree planting considerations to maximize net energy savings. Quantifying the ability of trees to reduce building carbon and financial expenses would be valuable both for justifying a large campus tree presence and for improving the sustainability of campus buildings. Further, this research direction could be integrated into an updated University Sustainability Plan in Area 1 (Climate Change and Energy) and Area 2 (High Performance Buildings).

Natural Environment

A third potential research avenue is to quantify campus biodiversity benefits of trees (in other words, to analyze the ecological communities on campus that are connected in some way to trees). i-Tree Eco is currently unable to analyze habitat provisions and functions, but this ES should still be evaluated with alternate methods on campus as it is predicted to remain impactful in a changing climate. Understanding the various roles trees play in the campus ecological community and their contribution to forest resilience would strengthen arguments for planting and retaining trees of all different species and characteristics. Student and community engagement would tie in neatly with this research direction. Student, faculty, and community volunteers could contribute to biodiversity data collection by reporting any animals that they observe on or around UChicago trees through an app or online site. A UChicago “Bio Blitz,” or 24-hour challenge of biodiversity cataloging, could also be held to document campus species and amplify interest in the ecological functions of trees. Efforts could be made to integrate data collection and/or data analysis for this research avenue into University coursework or extracurriculars. Additionally, signage for campus areas of high biodiversity could be created and posted to display fun ecological facts or Chicago/campus-specific ecological information. Studying trees and their role in UChicago’s biodiverse community would give Facilities and residents a better understanding of the ecosystem they inhabit, and thus strengthen the case for protecting and enhancing it.

Acknowledgements

We would like to thank the following individuals and institutions for their support and contributions to this project:

- Key Stakeholders: Professor Alison Anastasio and Kathleen Golomb for guiding the direction of this project, contributing useful resources, and providing thoughtful edits to the report.

- Graduate Lead: Chelsea Pauga for sharing expertise and providing edits to the report.

- Facilities Services Data Analysis: James Novack for compiling and cleaning tree inventory data.

- Environmental Frontiers Campus: Diana Petty and Professor Sabina Shaikh for spearheading Summer 2021 project work.

- Center for Robust Decision Making on Climate and Energy Policy: Emily Padston for continued interest in the project.

- University of Chicago Faculty: Professors Luis Bettencourt and Mark Berman for guidance on future project directions.

- The Morton Arboretum: Dr. Chai-Shian Kua, Megan Dunning, and Michelle Catania for providing expertise and informing the content of this project.

Appendix A: Ecosystem Services Descriptions

A.1 Carbon Storage and Sequestration

Carbon storage and sequestration, or carbon uptake more generally, is a well-known tree ecosystem service. Plants produce usable energy through photosynthesis, effectively turning reactant molecules of CO_2 into biomass like leaves, flowers, bark, and roots (McPherson, 2007). Carbon sequestration refers to the rate of this photosynthetic process, while carbon storage denotes the total amount of carbon molecules present within the tree. In other words, a tree's biomass is roughly equivalent to its total amount of stored carbon (McPherson, 1998). Studies report that around 20% of a tree's carbon is stored in its roots (Johnson & Gerhold, 2003), though this may be an overestimate for urban trees (Schwendenmann & Mitchell, 2014) due to often-constrained root systems. Carbon sequestration rate depends on a variety of physiological factors like tree species, age, density, size at maturity, and growth rate, among others (Nowak et al., 2002). Scharenbroch (2011) encourages diverse forests that can withstand pests and disease for maximum carbon storage; generally, the healthier and more age-diverse a forest, the larger its carbon benefits.

Though urban forests sequester low amounts of carbon per unit area due to low density, individual urban trees sequester high amounts of carbon due to large size (Goodwin, 2012). In fact, Nowak (1994) reports that large trees (>77cm diameter) sequester 90x and store 1000x more carbon than small trees (<8cm diameter). For long-term carbon storage benefits, studies advise a forest of mixed ages (Norman & Kreye, 2020). When trees die, most stored carbon is re-released into the atmosphere through decomposition while a limited amount remains in the soil (Nowak et al., 2002). Prolonging tree life is thus a crucial aspect of maintaining the carbon storage properties and ecosystem benefits of an urban forest.

While trees do act as carbon sinks, tree planting and maintenance activities (e.g., electric pruning machinery, transportation) are sources of carbon. Emissions from such activities must be outweighed by stored carbon in order to render an individual tree a net carbon sink. The point at which total carbon emission surpasses total carbon sequestration is defined as the "Last Positive Point" (LPP), and much urban forestry effort is paid to delay or prevent trees from reaching it (Nowak et al., 2002). Allowing trees to live out their full growth potential through proper planting and care is crucial in establishing an urban forest of carbon sinks (Nowak et al., 2002). Adopting energy-conserving planting and maintenance practices (e.g., using handsaws and rakes instead of chainsaws and leaf blowers) and long-term carbon storage products (e.g., wood furniture) are also valuable actions in lowering the carbon footprint of urban trees (Davies et al., 2011; Nowak et al., 2002). Additionally, carbon sequestration is provided largely at the forest scale; in an urban setting, forest sequestration is low due to low tree density. UChicago's urban forest accordingly annually sequesters a negligible amount of carbon. Incorporating knowledge of the impact of carbon storage/sequestration and how to offset tree-related carbon sources will be impactful in future UChicago forest management decisions.

A.2 Air Pollution Mitigation

Trees are valuable for improving air quality, primarily through removal of gaseous pollutants. In an urban setting, air quality improvement is one of the most impactful ecosystem services due to the abundance of pollution from city infrastructure, transportation, and human inhabitants. Trees remove pollutants like NO_2, SO_2, O_3, CO, and PM10 (Hirokawa, 2011) through deposition to leaf surfaces (filtering of air) and stomatal uptake (Grote et al., 2016). The pollution removal, degradation, and stabilization process is often called phytoremediation (USDA Forest Service, 2019). If no damage to internal cell membranes occurs, pollutant uptake increases proportionally with outside pollution concentrations (Grote et al., 2016). Absorbed gaseous pollutants then "diffuse into intercellular spaces," forming acids with water films or reacting with inner-leaf surfaces (Nowak et al., 2018). It is key to note that for pollutants, similar to carbon, trees are not the final stop; the molecules eventually mobilize to the soil or atmosphere (Nowak et al., 2018). Trees are thus only one significant factor in reducing air pollution, though they can be an effective strategy for ameliorating air quality retroactively (i.e., once anthropogenic sources already release pollution).

Pollution mitigation depends on a myriad of factors like tree community structure (species, position), canopy structure (height, shape, size, density), and foliage structure (shape, surface texture), as well as tree health, soil moisture, meteorology, pollutant concentrations, and more (Baró et al., 2014; Grote et al., 2016; Nowak et al., 2018; Salmond et al., 2014). Leaf surface area is one of the most significant indicators of pollution mitigation potential, with large leaf surface areas removing "60-70x more gaseous pollutants" annually than trees with small leaf surface areas (Salmond et al., 2014). Pollution removal rates also increase when leaf surfaces contain wetness, salts, or ions, especially if the pollutant is water-soluble (Grote et al., 2016). It is also possible for pollutants to become "encapsulated or immobilized" in a leaf's wax layer during growth (Hofman et al., 2014, as cited in Grote et al., 2016). Certain tree species uptake pollutants more efficiently than others, like anisohydric species (extended stomatal opening; e.g., northern red oak (*Quercus rubra*)) rather than isohydric species (early stomatal closure; e.g., sugar maple (*Acer saccharum*)) (Roman et al., 2015). Additionally, pollutant removal is seasonal due to the seasonality of pollution concentrations and tree biology; during spring and summer, trees uptake more pollutants on average than during winter (Baró et al., 2014). For urban trees, specifically, pollutant mitigation is highest during daytime of the in-leaf season (Nowak et al., 2018). Understanding the range of nuanced factors in urban tree pollution mitigation is crucial in planting and maintaining an urban forest that improves local air conditions.

Tree pollution effects, much like carbon sequestration, are neither simple nor purely beneficial mechanisms. Too much gaseous pollution can cause excessive deposition to plant surfaces and block light needed for photosynthesis (Delegido et al., 2014, as cited in Grote et al., 2016) or cause vegetation damage and stomatal closure (Baró et al., 2014). Trees themselves can also be emitters of pollutants, as discussed in Section 1.4: Ecosystem Disservices Overview. Though it is much less impactful than the pollution alleviation of trees, plant emission of biogenic volatile organic compounds can contribute to ground-level ozone and PM2.5 formation, decreasing air quality and contributing to health complications (Salmond et al., 2014). While plants contribute to as much as 2/3 of VOC emissions (Naranjo, 2011), emission sources are difficult to disentangle and the magnitude of tree contributions to pollution is minor compared to the magnitude of anthropogenic contributions. An additional common air pollutant is pollen released by wind-pollinated tree species, which can cause mild to severe allergies among humans. Pollen concentrations are elevated in urban areas and may increase when high pollution concentrations are present (Grote et al., 2016; Salmond et al., 2014). Urban trees should thus be studied and incorporated in management considerations as both significant aids to air quality and as a minor source of pollution themselves.

A.3 Stormwater Runoff Management

Managing stormwater runoff is a top priority in urban areas due to the abundance of impervious substances like sidewalks, streets, and parking lots. While cities typically rely on gray infrastructure (pipes and wastewater systems) to handle stormwater runoff, large increases in runoff volume (for example, during major storm events) can contribute to overflow, which causes sewer system impairments, local flooding, and contamination of freshwater sources (Roy et al., 2014). To soften the burden on gray infrastructure, researchers suggest that urban areas incorporate green infrastructure like trees, rain gardens, bioswales, and permeable pavements that promote infiltration (Shuster, Morrison, & Webb, 2008). Trees are a promising candidate to reduce stormwater runoff because they supply reasonably compact vegetation in small areas with expansive canopies and root systems that effectively secure and pump considerable amounts of water through infiltration (Berland et al., 2017).

One mechanism of decreasing stormwater runoff in urban landscapes is tree infiltration, which is the movement of surface rainwater into soil for filtration. An experiment by Amorson et al. (2013) documents that even small trees contribute to a 62% decrease in runoff from asphalt, while other reports explain that trees improve infiltration by adjusting soil ecosystems through root growth (Bartens et al., 2008). Rainfall and runoff enter into soils differently depending on site conditions (Endreny & Collins, 2009), which is considered when selecting locations in which to plant trees.

Another way that trees aid in stormwater management is through canopy interception loss. Canopy interception loss, most relevant during and immediately after a storm event, refers to the sum of water evaporated from tree surfaces and stored in tree canopies. Canopy interception loss is measured through subtracting the sum of stemflow (i.e., water that runs down a tree's trunk) and throughfall (i.e., the water that drips through the canopy onto the ground) from the overall precipitation that a tree receives. Stemflow itself actually weakens rainfall intensity by slowing the rate of stormwater travelling to the tree's roots (Tanaka et al., 1996). According to Asadian & Weiler (2009), this interception loss contributes to a reduction of the volume of stormwater runoff, soil erosion, and pollutant removal, as well as an increase in protection of water quality. Canopy interception loss also depends on a variety of factors such as differences in bark thickness and roughness, mature size, leaf and branch angles, and leaf area and smoothness (Xiao & McPherson, 2016). Additionally, the time, duration, and intensity of a storm play roles in a tree's ability to intercept stormwater. Some studies note that interception loss is at its peak during the beginning phases of a storm but decreases as leaves become saturated with water and rainfall becomes excessive (Xiao et al., 2000). As a result, canopy interception loss is more strongly associated with water quality protection than intercepting stormwater.

Finally, it should be noted that trees manage stormwater runoff by capturing and releasing stormwater through evapotranspiration. Evapotranspiration refers to the evaporation of water from tree surfaces along with the transpiration of water from soil into the atmosphere via plants. Evapotranspiration plays a crucial role in the urban hydrological cycle, as represented in the water balance equation (precipitation = runoff + evapotranspiration + change in soil storage) (Peters et al., 2011). Consideration of the urban hydrologic cycle in stormwater management decisions is integral in mitigating the effects of sewage overflow, high pollutant loads, flooding, and high runoff volume.

A.4 Urban Microclimate Regulation

Microclimates refer to the climate of a small or specific local area that has set conditions different from its surrounding areas. Most urban environments contain microclimates with increased air and surface temperatures, solar radiation, humidity, and sudden wind speed changes (Akbari & Taha, 1992), all caused by anthropogenic sources. These urban microclimates are usually found in multiple spots within cities and could range in size from a few blocks to a section of one street. On an urban university campus such as UChicago, there are multiple, small microclimates. Urban environments and cities increase surrounding air temperatures because surfaces such as asphalt and concrete have high heat capacities. As a result, these surfaces retain heat during the day and slowly release it at night, leading to overall increased ambient temperatures (Dimoudi, 2013). The urban environment with increased temperatures caused by human-made inventions is a phenomenon known as the urban heat island effect. Trees can ameliorate urban microclimate effects by providing numerous benefits such as cooling air through evapotranspiration, shading, reducing wind speeds, and preventing solar radiation from heating surrounding buildings (discussed further in Section A.5: Building Energy Effects). This amelioration immensely boosts pedestrians' wellbeing and overall urban experience.

In particular, urban trees provide the unique service of outdoor thermal comfort for city-dwellers. One way that urban trees affect air temperature is by shading with their canopies, which helps block thermal radiation from the sun while cooling the local area and surface grounds. The size of tree canopies affects air temperature as well; closed canopies (i.e., leaves and branches closer together) tend to decrease temperatures more than open canopies because less sunlight can penetrate through (Sanusi et al., 2017). However, branches that hang further down limit air movement and cooling during the night, leading to warmer temperatures (Souch, 1993). Trees also regulate microclimates through evapotranspiration, a process by which water is evaporated from soil and transpired from plants, allowing trees to cool nearby environments (Taha, 1997). Trees act as a natural cooling agent for urban environments and are therefore essential for lowering air temperatures in microclimates.

Another benefit trees provide is protection against sudden changes in wind speed. Trees with wider crowns located in areas with high-velocity winds mitigate the downwashing wind effect (i.e., when wind blows straight down onto pedestrians after travelling into the surface of a building) (Hosseinzadeh & Keshmiri, 2021). Placing trees as close to buildings as is feasible without stunting root growth would also help mitigate the corner wind effect (i.e., when wind reaches the sharp edge of a building and picks up speed). Tree provision of wind protection is beneficial, as microclimates in urban settings are often disturbed by sudden changes in wind speed. Overall, urban trees' regulation of microclimates by combatting the urban heat island effect, providing thermal comfort to humans, and protecting against unexpected wind speed changes should be incorporated in urban planning to improve the pedestrian experience.

A.5 Building Energy Effects

Trees have the potential to reduce the amount of energy consumed by nearby buildings in several ways, but most effectively through summer shading. During warm parts of the year, trees absorb solar radiation that would otherwise be absorbed by building facades, thereby lowering inside temperatures, reducing building cooling loads, and lowering energy consumption from air conditioning systems (Abdel-Aziz et al., 2015). This cooling is directly related to foliage density (Pandit & Laband, 2010) and planting pattern (Tsoka et al., 2021): a continuous, dense tree canopy corresponds to higher energy savings. In a seasonal climate such as Chicago's, the largest effects of shading are felt in the summer months, when the greatest amount of solar radiation is received. On the other hand, shading in winter months can be detrimental because it can add to building heating loads. Strategic planting of deciduous trees, propose Escobedo et al. (2009), lessens the amount of solar radiation blocked by trees in the winter, thereby increasing net energy savings. Similarly, placing trees on the south side of a building maximizes surface area for winter solar heating (Escobedo et al., 2009).

Through their role in the regulation of microclimates, trees contribute to additional cooling and warming which can further reduce buildings' temperature-related energy consumption. When tree leaves perform transpiration, they release water into the surrounding air; as the water evaporates, the air cools (Trees-Energy-Conservation, 2019). The cooling that trees produce from evapotranspiration does not generally add to building heating loads in the winter, as deciduous trees are bare (Abdel-Aziz et al., 2015). Another way that buildings can benefit from the presence of trees in warmer parts of the year is through air quality improvements; by removing pollutants, trees can alter local temperatures and lower building cooling loads (Nowak et al., 2018). Finally, in colder months, trees can affect energy consumption by blocking harsh winds. Their placement around a building can direct airflow toward or away from the building, depending on the desired effect (either cooling the building in warm months or lessening cooling in cold months) (Escobedo et al., 2009).

It is necessary to note that not all trees will have equal building effects, as evapotranspiration rates, air pollution removal rates, shading, and wind blocking differ based on a number of factors including tree species, maturity, and placement. According to Livesley et al. (2016), evapotranspiration rates from mature trees with high stem density would be most likely to lower the temperature of an urban area, while the exact number of trees required would depend on their species. Thus, both the individual tree and its role in the larger urban forest are necessary to consider when planning to decrease building energy consumption, lower carbon emissions, and save money.

A.6 Noise Attenuation

Urban environments are subject to high levels of noise from vehicles, construction, and dense human populations, and trees are one passive method of lessening noise and its detrimental effects on communities. Sakieh et al. (2017) report a "highly meaningful linkage" between urban acoustic noise and pollutant concentrations, which highlights how trees directly provide benefits in urban areas. Mechanistically, plants reflect, refract, scatter, and absorb sound with their foliage (Fan et al., 2010). Attenuation effects depend on a variety of tree factors (arrangement, density, height), leaf factors (size, shape, tactility, weight), and bark factors (thickness, age, roughness) (Fan et al., 2010; Fang & Ling, 2003; Li et al., 2020). Fan et al. (2010) report that different attenuation frequencies align with different tree species, so designing urban green spaces with diverse trees and complementary noise-reducing spectra will enhance noise reduction. A 2020 study by Li et al. (2020) reports that conifers (*Pinophyta*) are the most experimentally effective tree at reducing noise, while larch (*Larix*) are the most effective tree at absorbing noise with their bark (Kniver, 2020). Studies also observe a strong association between leaf shape and sound reduction, with ovate or elliptic leaves having higher reduction capabilities (Fan et al., 2010). Higher leaf tactility, too, correlates with heavier leaf weight, larger plant biomass, and increased noise attenuation (Fan et al., 2010). Fang and Ling (2003) claim that tree visibility (i.e., density) is the most significant parameter for noise reduction, and accordingly promote tree belts of at least 30m in depth for the greatest noise reduction benefits. Li et al. (2020) clarify that tree belt density is constrained by tree species selection, so species is a crucial factor when planning green areas that reduce noise (Kniver, 2020).

In addition to lowering city noise levels, trees boast natural sounds (e.g., birds, rustling of leaves) that increase people's perception of soundscape quality and improve overall mood (Salmond et al., 2014). For maximum reduction of traffic-related noise, Sakieh et al. (2017) suggest planting trees and establishing green areas adjacent to roadways and other noise pollution sources. Noise attenuation is a unique tree service that can improve city and campus soundscapes by quieting anthropogenic sounds and heightening natural noises, and is deserving of future consideration in landscape management.

A.7 Habitat Provision and Functions

Trees play a crucial ecological role in urban environments and are considered keystone structures because of the many ecosystem functions they provide. Manning et al. (2006) outline a comprehensive list of these ecological functions, which includes increasing local soil nutrients and plant species richness, enhancing primary productivity, providing shelter, shade, and foraging habitats to both canopy- and ground-dwelling animals, enhancing landscape heterogeneity that increases landscape-scale species richness, and providing ecological continuities such as biodiversity and ecosystem resilience. Several ecological studies of trees in urban settings have focused on their impact on wildlife, including Stagoll et al.'s investigation of trees in urban parks and their relationship to bird diversity (2012). The researchers found that not only did trees have a strong, positive relationship with bird diversity, but that as trees increased in size, their positive effect on bird diversity also increased. The same study emphasized that trees as small as 40cm in diameter (smaller than recommended by many management authorities) can encourage bird diversity, demonstrating that even small tree presence can be integral in fostering bird communities. Trees also provide habitats for ants and other arthropods, as highlighted by Yasuda and Koike (2009), who found that tree size is a significant element in arthropod diversity. This evidence should be considered in the face of tree replacement: removing habitat structures hinders the survival of their inhabitants, disrupting the local ecosystem. Maintaining keystone structures like trees promotes biodiversity critical to ecological resilience in urban areas (Le Roux et al., 2014).

Healthy, biodiverse urban ecosystems are beneficial for a number of reasons, many of which overlap with other ecosystem services: they increase ecological sustainability, enhance human health and well-being, and can help contribute to climate change mitigation and adaptation. Cities with abundant and biodiverse public green spaces also provide opportunities for education about sustainability and the natural world (Schewenius et al., 2014). Universities may make use of this by highlighting campus biodiversity and its benefits in coursework, research, and outdoor programming such as Arbor Day tree walks and "Bio Blitz" events, where participants race to identify as many local species as they can within 24 hours. In these ways, the habitat functions of urban trees extend their benefits beyond the natural world, establishing what may initially seem unrelated to human well-being as an impactful ecosystem service to consider in urban planning.

A.8 Human Health Benefits

Beyond the positive health effects associated with improved air quality and shade, trees provide numerous mental, physical, and community health benefits, such as psychological relaxation. Bielinis et al. (2018), for example, found that 15-minute-long sessions of "forest bathing," or taking in and interacting with a forest atmosphere, significantly improved the mood of young adults by inducing feelings of restoration and vitality. Exposure to urban vegetation is similarly impactful, and something from which people of all ages can benefit. After a 20-minute walk through a park, children with attention deficit disorders concentrated better and were more alert than those who had walked through downtown areas, according to Taylor and Kuo (2009). Urban vegetation also shows an inverse relationship to children's body mass index, and proximity to green space has been linked to lowered rates of mortality (both in general and specifically from circulatory diseases) and improved longevity in adults (Pataki et al., 2011).

Additionally, trees—rather than green space in general—are uniquely beneficial to mental and physical health. In an urban setting, Astell-Burt and Feng (2019) demonstrated that exposure to large tree canopies was associated with almost a third lower incidence of psychological distress, as well as lower incidence of "fair to poor" general health; Kardan et al. (2015) similarly found that people who live in areas with higher street tree density report significantly higher health perception and fewer cardio-metabolic conditions. They found that 10 additional trees on a city block, an increase in annual income of $10,000, or a decrease in age by 7 years improved health perception in the same way. 11 additional trees decreased cardio-metabolic conditions in the same way that an increase in annual personal income of $20,000 or being 1.4 years younger did (Kardan et al., 2015). Strikingly, while walkable greenspace is beneficial, the positive effects of trees are not limited by a person's ability to physically interact with the natural environment. In many cases, just a view of trees is beneficial. Ulrich (1984) showed that hospital patients with a view of trees had shorter postoperative stays, received fewer negative nurse's notes, and received weaker and fewer pain medications than did patients with views of a brick wall. Similarly, Matsuoka (2010) found that views with more trees in school cafeterias and classrooms, and larger windows themselves, corresponded to better high school student academic and behavioral outcomes, including higher graduation rates and lower incidences of disorderly conduct and criminal activity. In particular, landscapes composed primarily of trees and shrubs were associated with greater student performance than landscapes of mowed grass and parking lots. Several theories have been proposed to explain the positive effects of trees on physical and mental health: physical activity encouraged by proximity to walkable greenspaces like parks (Takano et al., 2002), cognitive and emotional responses to views of and interactions with nature (resulting in positive feelings and stress relief) (Bielinis et al., 2018; Matsuoka, 2010; Ulrich, 1984; Berman et al., 2008), and aesthetic preference for heterogeneity in views of nature (which is effectively established by trees, unlike grasses and shrubs, and thought to increase one's sense of well-being) (Matsuoka, 2010).

Finally, a major impact of trees is their effect on community health, including lower crime rates and greater food security (in addition to the better high school student outcomes already discussed). While there has been conflicting evidence on the topic, Kuo and Sullivan (2001) showed that, in inner-city Chicago, the amount of vegetation around public housing complexes is negatively associated with crime rate. To explain this result, they proposed that green spaces increase informal surveillance because they receive greater foot traffic, and also mitigate some of the psychological precursors to violence. Biodiverse urban food systems can also enhance food security, as shown by Clark and Nicholas (2013), who report that urban agriculture is a global strategy to improve food security by providing access to nutritious food and income from food sales and employment. Agriculture and urban forestry have historically remained separate but combining elements of each into "urban food forestry," or the use of woody perennial fruit- and nut-producing tree species in urban landscapes, has the potential to improve the sustainability of urban communities. Such incorporation of ES into urban landscapes is strengthened by the use of multifunctional species that also improve air quality, regulate microclimates, and provide habitats, among other benefits. Furthermore, engagement in urban food forestry and other urban greenspace interactions can help facilitate a sense of community among residents of urban areas, increasing social cohesion (Jennings & Bamkole, 2019). Thus, trees benefit community health in addition to individual mental and physical health and can be integrated into University student wellbeing and landscape design plans accordingly.

A.9 Aesthetic Quality Improvement

Beautification and aesthetics are significant ecosystem services provided by trees, and often have cultural meaning to individuals and communities. Since aesthetic value is difficult to quantify, researchers measure beauty in unique, often qualitative ways. According to Wang et al. (2019), trees magnify aesthetic quality due to their calming nature and restorative potential. An increase in tree biodiversity causes the environment to become more complex and fascinating to the human eye in comparison to flat landscapes or tree monocultures (Kaplan, 1995). Additionally, studies show that people positively associate biodiversity with scenic beauty (Parsons & Daniel, 2002). Diverse forests bring visitors serenity while simultaneously enhancing imagination, especially in children and adolescents. Urban green spaces that prioritize aesthetics can also provide benefits like opportunities for exercise, recreation, and relaxation, which in turn creates a sense of place and identity (Shackleton & Blair, 2013). One study utilized sacred urban green spaces as a method to measure aesthetic preferences and found that most respondents specifically associated the presence of larger trees with aesthetic satisfaction (De Lacy & Shackleton, 2017).

While the aesthetic benefits listed above are harder to quantify and empirically evaluate, beautification can potentially be measured by using property values through a hedonic price method. Studies indicate that an increase in greenery and trees in neighborhoods improves their aesthetic quality, which in turn increases willingness to pay for nearby residential properties (Wachter & Wong, 2008). Additionally, people are more willing to purchase homes in areas with public trees rather than areas with trees just on private property (Pandit et al., 2013). A public space with trees is valuable to those who wish to benefit from aesthetics without incurring maintenance costs and disamenities such as pruning, thinning, blocked views, dropped leaves, and damaged pavements (Donovan & Butry, 2010). Overall, trees should continue to be considered for their aesthetic value in landscape plans due to their services to the community of promoting human fulfillment and improving scenic quality.

A.10 Oxygen Production

Oxygen production is a familiar and oft-mentioned ecosystem service of trees. Oxygen enables life: plants intake CO_2 and release O_2 in photosynthesis while organisms intake O_2 and release CO_2 in respiration (Mitra, 2017). Net oxygen production is measured by subtracting the amount of consumed oxygen during plant respiration from the amount produced during photosynthesis (Nowak et al. 2007). Using this method, Nowak (2007) concluded that the average amount of trees needed to offset one human adult's oxygen consumption per year was 30 trees. Despite its necessary role in sustaining life, oxygen production is not a significant ecosystem service when compared to the other ES urban trees provide. There is a vast, relatively constant amount of atmospheric oxygen present on Earth, estimated at 1.2 quadrillion tons O_2. Given the utter volume of oxygen, burning all trees would only decrease the atmospheric oxygen concentration by a few percent (Broecker 1970), effectively rendering the oxygen provided by urban trees as negligible. Therefore, oxygen production should remain inconsequential in University management considerations.

Appendix B: Climate Change Ecosystem Service Effects

While some ecosystem services (e.g., carbon storage/sequestration, microclimate regulation) are better studied in regard to climate change, others (e.g., noise attenuation) are lacking in future-focused data. In order to better understand the potential impacts of climate change on our campus ES, we consolidate and discuss the existing literature on global change and ES effects in the categories of carbon storage/sequestration, microclimates, human health benefits, and habitat provisions and functions. Five of the remaining ecosystem services (air pollution mitigation, stormwater management, building energy effects, noise attenuation, aesthetic quality improvement) are not reported due to a lack of studies in regard to climate change, and the last remaining ecosystem service (oxygen production) is omitted due to its minimal utility. Understanding the potential effects of climate change on ES is invaluable because, simply put, more trees provide more ES; climate-driven damage to individual trees lessens the overall provision of ES by an urban forest. To foster a campus forest with minimal ES losses requires such a review of current models and climate research.

B.1 Carbon Storage and Sequestration

Increasing atmospheric carbon dioxide (CO_2) concentrations and associated warming lead to a variety of environmental effects. One likely effect is an increase in net primary productivity (NPP), stimulated by reactive nitrogen deposition and fertilization (Ordóñez & Duinker, 2014; Pretzsch et al., 2017; Solomon & Kirilenko, 1997; Van Houtven et al., 2019; Zaehle et al., 2007). Net primary productivity is defined as the rate of energy storage by plants, or the amount of CO_2 taken up in photosynthesis minus the amount of CO_2 released during respiration (NASA Earth Observatory, 2016). Nitrogen deposition may be more significant than warming in increasing NPP and carbon storage, suggests Van Houtven et al. (2019). Zaehle et al.'s 2007 European modeling study predicts that initial NPP (carbon uptake) by trees will increase with increasing carbon emissions, rendering trees net carbon sinks until "at least 2040." Increases in carbon storage could be more profound at the mid-to-high latitudes, where photosynthesis has previously been limited by cold temperatures (Meineke et al., 2016; Pretzsch et al., 2017). Rötzer et al. (2019) also predict a general rise in mean annual total tree biomass for European cities. Warming could also extend tree growing seasons, leading to more annual growth (Locosselli et al., 2019; Meineke et al., 2016; Pretzsch et al., 2017). Pretzsch et al. (2017) justify this trend by reporting that high urban tree growth rates have accompanied climate change since 1960. Some species grow faster under elevated temperatures than others, and a 2010 study by Way and Oren found that deciduous trees outgrew evergreen species in warmer conditions. CO_2-fertilization may also indirectly favor growth, potentially by increasing trees' water efficiency, report Zaehle et al. (2017).

Despite initial carbon storage gains from increased NPP, most studies predict overall tree carbon losses from the detriments of warming, beginning between 2040-2070 (Breshears et al., 2011; Pretzsch et al., 2017; Solomon & Kirilenko, 1997; Zaehle et al., 2007). Researchers predict that warming and urban impervious surfaces will strain trees' water availability (Breshears et al., 2011; Meineke et al., 2016; Rötzer et al., 2018; Zaehle et al., 2007), leading to increased litterfall and decomposition. One common mechanism of water stress associated with warming is a decline in "stomatal conductance", explained by isohydric trees closing their stomata to reduce water loss through transpiration when under stress (Meineke et al., 2016; Rötzer et al., 2018). Not all trees regulate stomata to help during periods of water stress, as evidenced by anisohydric species; this is largely because closing the stomata reduces photosynthesis. Another effect of urban warming is lower basal area growth, which reduces the amount of carbon stored per tree (Meineke et al., 2016). Urban warming also reduces tree growth and size at the start of each subsequent growing season, leading to shallow growth trajectories. Meineke et al.'s case study of Raleigh, NC (2016) reports that the direct effects of warming caused a 12% reduction in urban tree carbon sequestration in 2014. In moderate and high greenhouse gas emissions scenarios, trees may indeed become net sources of carbon to the atmosphere, despite any initial uptake benefits from primary productivity.

Another potential factor in carbon storage/sequestration is lowered nutrient availability, which studies predict will limit carbon uptake on a long-term scale due to lower biomass growth (Breshears et al., 2011; Rötzer et al., 2018; Zaehle et al., 2017). Locosselli et al. (2019) report that higher phosphorus concentrations are beneficial to trees, though often limited in city soils. Van Houtven et al. (2019) emphasize the significance of nitrogen, an often-limiting nutrient in terrestrial soils, on growth. Low nutrient availability will diminish plant growth, leading to further-lowered soil nutrients from less biomass decomposition. Future reductions in tree cover (and the associated litterfall) due to higher temperatures, extreme weather events, and increased disease/pest infections will likely alter soil composition as well. Disruption to mycorrhizal communities (i.e., beneficial root microorganisms) from changing biomass decomposition rates can also trigger high soil erosion rates, in turn altering soil biogeochemical cycling that results in carbon losses (Breshears et al., 2011). High air pollution in cities may also contribute to lowering the carbon storage and sequestration of urban trees (Pouyat et al., 1995, as reported in Schwendenmann & Mitchell, 2014). Ordóñez & Duinker (2014) report that warming will likely heighten air pollution and seasonal climate variability, causing slower growth rates and higher stress in trees. Smaller and more strained trees have lower NPP, and thus lower carbon uptake. Additionally, extreme climate events may disrupt carbon storage/sequestration. Droughts and severe temperature highs/lows may offset years' worth of sequestration in only one year, according to Zaehle et al. (2017). Phenological disruptions may also occur as a result of initial tree growth bursts, such that pollinators and seed dispersers may not spread trees as effectively (University of Chicago Associate Professor, personal communication, August 11, 2021). Pest outbreaks, too, will likely be favored by warmer temperatures. A study by Meineke et al. (2016) found that hotter trees had up to 56x more spider mites than cooler trees and general increased arthropod abundance, which led to reduced tree branch growth and less carbon storage.

Together, the factors predicted to accompany climate change can lead to "artificially shortened lifespans" for urban trees (Nowak et al., 2004, as cited in Ordóñez & Duinker, 2014). Shorter tree lifespans raise the likelihood of reaching the LPP (Appendix A.1: Carbon Storage and Sequestration), and thus increase the amount of trees acting as net carbon sources, rather than sinks. Meineke et al. (2016) explain that urban forest carbon storage losses compound annually, causing ever-lowering carbon benefits with warming. Furthermore, carbon sequestration, much like other urban forest ES, is only impactful when there are many trees providing the service. Predicted tree stress and mortality from climate change thus decreases the total amount of carbon uptake by urban forests, and therefore lowers the positive impact of the ecosystem service.

B.2 Urban Microclimate Regulation

Modern urban heat islands (cities) benefit from trees' provision of cooling, shading, and wind-reducing effects. Increasing global temperatures are set to heat up both cities and their trees, potentially by as much as 1.64ºF per decade (Voogt, 2002, as cited in Corburn, 2009). Even in moderate climate scenarios, research indicates that urban heat islands are expected to increase in severity and prevalence (Corburn, 2009; Ordóñez & Duinker, 2014). Much like with the ES of carbon storage/sequestration, climate change may initially favor urban trees. The heat, nitrogen deposition, and ozone concentration of cities may initially extend tree growing seasons by up to 8.8 days per year, report Pretzsch et al. (2017). Growth rate in general also increases with urban heat (Locosselli et al., 2019; Meineke et al., 2016; Pretzsch et al., 2017), though Locosselli et al. report that high temperatures during the previous growing season lead to reduced growth rates the following year. The researchers also report that, presently, global climate change accelerates tree growth by 21% and the urban heat island effect accelerates growth by 14%, as seen in tree ring patterns (measured using a technique called dendrochronology). Increased growth rate favors early provision of many ES but also earlier tree aging and replacement.

Despite faster growth, temperature swings and increased wind and weather intensity can cause tree stress and mortality, leading to patchy canopies and an increased amount of radiation reaching the city ground (Breshears et al., 2011; Ordóñez & Duinker, 2014). Breshears et al.'s 2011 study estimates that tree cover reductions in cities could be as large as 25-40%. While primary productivity and rapid growth may be favored in urban environments, stressor confluence is predicted to ultimately cause tree mortality, exacerbating the urban heat island effect and causing cities to become larger carbon sources.

Ordóñez & Duinker (2014) predict that cities will be also affected by long-term resource problems like water scarcity and increased air pollution. Nelson et al. (2013) report that the U.S. Midwest is expected to experience more frequent droughts during the growing season and excessive precipitation during the remainder of the year, harming tree growth and stability. Urban humidity regimes generally mimic drought conditions, subjecting urban trees to significant water stress (Ordóñez & Duinker, 2014). Hotter microclimate temperatures may also lead to higher soil evaporation rates and moisture disruptions from changes in "precipitation interception," thereby altering decomposition rates (Murphy et al., 1998, as cited in Breshears et al., 2011). Larger trees (which confer the most ES benefits) have difficulty getting enough water in urban environments (Pretzsch et al., 2017), and may live shortened lifespans. Additionally, Ozone (O_3), particulate matter (PM10), and metal particles can accumulate on leaves and hinder photosynthetic systems, gas exchange, and stomatal functioning (Locosselli et al., 2019). Locosselli et al.'s 2019 study found that tree growth rate decreases with higher concentrations of PM10, which is a major pollutant from industrial activity in cities. Elements like aluminum, barium, and zinc also negatively impact tree growth due to toxicity, growth limitations, root interference, disruption of essential nutrient uptake, and altered enzyme functioning (Locosselli et al., 2019). The already-difficult conditions of urban trees (limited water availability, low soil quality, excess heat, high pollution concentrations (Brune, 2016)) coupled with new climate stressors are predicted to cause phenological tree responses like the advanced onset of growth phases, extension of initial growth seasons, and shortening of later growth seasons (Pretzsch et al., 2017; White et al., 2002, as cited in Ordóñez & Duinker, 2014), decreasing trees' ability to provide expansive canopies. Lowered canopy area will in turn heighten the urban heat island effect, and the cycle of tree stress will become a positive feedback loop.

Researchers also predict that climate change will correlate with pest and disease prevalence (Meineke et al., 2016; Ordóñez & Duinker, 2014), which can decrease canopy area from infection and herbivory. Decreased canopy area decreases shading, evapotranspiration, and overall microclimate regulation. The close proximity of urban trees to each other and to carriers of international species (e.g., humans and imported goods) makes urban forests particularly vulnerable to invasive pest and pathogen outbreaks. Urban forests are also often homogenous and/or have areas of monoculture, rendering them more vulnerable to outbreaks due to easy transmission of species-specific pests/diseases (Ordóñez & Duinker, 2014). Pest and disease presence correlate with reduced urban forest canopy cover, increased tree mortality, and corresponding reductions in microclimate regulation (Donovan et al., 2013, as cited in Ordóñez & Duinker, 2014; Meineke et al., 2016).

B.3 Human Health Benefits:

Studies predict climate change's effects on trees to influence individuals and communities as well as cities and forests. The premature loss of large trees on properties (Breshears et al., 2011) can result in temporary reductions in privacy or in the hiding of unsightly items like equipment. Loss of symbolic or favored trees can also bring sadness and a sense of disconnection from one's environment (Breshears et al., 2011). Additionally, allergies are a commonly noted ecosystem disservice of trees, and one that is predicted to increase with climate change. Higher average temperatures and strong wind events may increase wind-pollination, thereby increasing the amount of airborne pollen. Climate change's effects on trees and humans must thus be viewed as impactful on large and small scales. However, many of the health benefits of trees are based on the presence of any trees, rather than many trees; this ES is more likely to persist in the face of climate change than ES dependent on high tree density.

B.4 Habitat Provisions and Functions

Some future-focused studies of trees predict reductions in tree cover after initial growth bursts (Meineke et al., 2016), which can lead to numerous effects on ecological communities. Ecosystems are carefully balanced, and alterations to tree and urban forest properties will likely cause disruptions in plant-animal dynamics and habitat quality (Breshears et al., 2011). It is difficult to predict the point at which a species of animal or tree will no longer be properly suited to its environment. If trees and their inhabitants become maladapted to their environment at different times or levels of warming, ecological disruptions will result. One indication of tree suitability to changing environments is the USDA PHZ (discussed in Section 2.3.2: USDA Plant Hardiness Zones), which reflects tree species range shifts. If an organism is a specialist on a single species of tree that is no longer suited to its environment, the organism may also undergo a range shift, adapt to other still-environmentally-suited tree species, or suffer from mortality. While range shifts can increase the amount of survivable land for some plants, as discussed in Section 2.3.2: USDA Plant Hardiness Zones, they can also push some species out of their original habitable states or countries. Additionally, many fruit and nut trees require a winter chill before a warm growing season, decreasing the quantity of food trees produce as winter temperatures increase (Luedeling et al., 2011, as cited in Nelson et al., 2013). Excessive heat or drought, too, may cause low food yield (Breshears et al., 2011), increasing animal competition.

Migration of temperature zones could potentially create new habitat ranges. Migration of tree belts may take much longer than zonal warming, however. Solomon & Kirilenko's 1997 modeling study found that “little measurable tree migration” would take place within the next 70-80 years of climate changes, leading to high tree mortality and carbon release to the atmosphere. The researchers’ results emphasize the uncertainty of future tree success, and therefore how animal species will have to rapidly adapt to changing ecosystems. Additionally, water stress and initial rapid tree growth are predicted to lead to loss of large trees that can no longer sustain their water and nutrient demands (Pretzsch et al., 2017). Fewer organisms may be able to inhabit the same trees, potentially increasing competition. Trees will remain keystone structures regardless of their location, and the changing success of their ecological communities will be seen with time.

Appendix C: Supplementary Tables

Genus	Species	Distribution area	ISO	MT	SQT	OVOC	References
Acer	*sp.*						c, n
	platanoides	N/C					c, t
	pseudoplatanus	N/C					w
Aesculus	*hippocastanum*	N/C					u
Betula	*pendula*	N/C					g, h, l ,r
Carpinus	*betulus*	N/C					a, m
Celtis	*occidentalis*	S					d, e
Fagus	*sylvatica*	N/C		•			l, o°, t
Fraxinus	*sp.*						t
	excelsior	N/C					a, c
	ornus	S					c
Picea	*abies*	N/C					f, l
Pinus	*sylvestris*	N/C					a, j, l, v
	pinea	S					y
Platanus	*acerifolia*	N/C, S					b
	orientalis	N/C, S					a, c, b
Populus	*sp.*						t
	nigra	N/C, S					c
	tremula	N/C, S					a, c
Prunus	*avium*	C					c, f
	serotina	N/C					c, f
Quercus	*ilex*	S	*				b*, l, p, t
	pubescens	N/C					t, y
	robur	N/C	•				b, l, o°, t
Robinia	*pseudoacacia*	N/C, S					b, c, r, t
Sophora	*japonica*	S					b, k
Tilia	*cordata*	N/C					c, t
	platyphyllos	N/C					c
Ulmus	*minor*	S					c

Table 7: Low BVOC Emitting Trees. *Column 4 of this table from Fitzky et al. (2019) represents oxygenated volatile organic compound emissions of urban tree species. Green cells represent low emissions, the yellow-green cell at the top right represents low-medium emissions, and gray cells indicate no available data. Aside from "Genus" and "Species," the remaining columns are not relevant to this report.*

Age Class	Definition (Bartlett Inventory Solutions, n.d.)
New Planting	A tree that is not yet established.
Young	Established tree that has not been in the landscape for many years.
Semi-mature	Established tree that has not yet reached full growth potential.
Mature	A tree within its full growth potential.
Over-mature	A tree that is declining or beginning to decline due to its age.

Table 8: Age Class Definitions According to Bartlett Inventory Solutions.

Condition Class	Definition (Bartlett Inventory Solutions, n.d.)
Dead	
Poor	Most of the canopy is affected with dieback, undesirable leaf color, leaf size and new growth. Parts of the tree are in the process of failure.
Fair	Parts of the canopy has undesirable leaf color, leaf size and new growth. Tree or parts of the tree are likely to fail.
Good	Tree health and condition is acceptable.

Table 9: Condition Class Definitions According to Bartlett Inventory Solutions.

Species (Scientific Name)	Species (Common Name)	Number of Trees
Gleditsia triacanthos	Honeylocust	470
Tilia cordata	Littleleaf linden	162
Fraxinus pennsylvanica	Green ash	163
Acer platanoides	Norway maple	125
Hybrid cultivars	Elm spp.	254
Quercus macrocarpa	Bur oak	93
Ginkgo biloba	Ginkgo	138
Celtis occidentalis	Hackberry	117
Acer freemanii	Freeman maple	103
Quercus bicolor	Swamp white oak	132
	Total	1757 (46.7% campus trees)

Table 10: Campus Frequency of "Important" Tree Species

Species (Scientific Name)	Species (Common Name)	Age Class			
		Young	Semi-mature	Mature	Total
Gleditsia triacanthos	Honeylocust	115	240	115	470
Tilia cordata	Littleleaf linden	18	112	32	162
Fraxinus pennsylvanica	Green ash	12	122	29	163
Acer platanoides	Norway maple	6	106	13	125
Hybrid cultivars	Elm spp.	76	154	21	251
Quercus macrocarpa	Bur oak	31	27	35	93
Ginkgo biloba	Ginkgo	76	54	8	138
Celtis occidentalis	Hackberry	62	40	14	116
Acer freemanii	Freeman maple	43	59	1	103
Quercus bicolor	Swamp white oak	102	27	1	130
	Total	541	941	269	1751

Table 11: "Important" Tree Species by Age Class

Species (Scientific Name)	Species (Common Name)	Condition Class			
		Good	Fair	Poor	Total
Gleditsia triacanthos	Honeylocust	373	79	18	470
Tilia cordata	Littleleaf linden	117	34	8	159
Fraxinus pennsylvanica	Green ash	96	50	16	162
Acer platanoides	Norway maple	57	38	28	123
Hybrid cultivars	Elm spp.	210	27	15	252
Quercus macrocarpa	Bur oak	63	23	7	93
Ginkgo biloba	Ginkgo	132	6	0	138
Celtis occidentalis	Hackberry	92	14	9	115
Acer freemanii	Freeman maple	87	15	0	102
Quercus bicolor	Swamp white oak	110	19	2	131
	Total	1337	305	103	1745

Table 12: "Important" Tree Species by Condition Class

Genus (Scientific Name)	Genus (Common Name)	Number of Trees
Gleditsia	Honeylocust	476
Quercus	Oak	444
Acer	Maple	401
Ulmus	Elm	259
Tilia	Linden	204
Ginkgo	Ginkgo	138
Celtis	Hackberry	119
Gymnocladus	Coffeetree	63
Platanus	Planetree	32
Catalpa	Catalpa	25
Taxodium	Baldcypress	16
Metasequoia	Dawn redwood	13
	Total	2190 (58.2% campus trees)

Table 13: Campus Frequency of Genera of Interest

Genus (Scientific Name)	Genus (Common Name)	Age Class			
		Young	Semi-Mature	Mature	Total
Quercus	Oak	203	191	47	441
Ginkgo	Ginkgo	76	54	8	138
Ulmus	Elm	76	155	25	256
Celtis	Hackberry	63	41	14	118
Gymnocladus	Coffeetree	50	13	0	63
Gleditsia	Honeylocust	117	241	118	476
Tilia	Linden	27	138	39	204
Acer	Maple	174	196	31	401
Taxodium	Baldcypress	7	7	0	14
Catalpa	Catalpa	0	23	1	24
Platanus	Planetree	11	12	9	32
Metasequoia	Dawn redwood	11	2	0	13
	Total	815	1071	286	2180

Table 14: Genera of Interest by Age Class

Genus (Scientific Name)	**Genus (Common Name)**	**Condition Class**			
		Good	Fair	Poor	Total
Quercus	Oak	311	104	26	441
Ginkgo	Ginkgo	132	6	0	138
Ulmus	Elm	212	29	16	257
Celtis	Hackberry	94	14	9	117
Gymnocladus	Coffeetree	59	4	0	63
Gleditsia	Honeylocust	378	80	18	476
Tilia	Linden	155	35	9	199
Acer	Maple	271	93	34	398
Taxodium	Baldcypress	14	2	0	16
Catalpa	Catalpa	19	5	1	25
Platanus	Planetree	21	8	3	32
Metasequoia	Dawn redwood	11	2	0	13
	Total	1669	382	116	2175

Table 15. Genera of Interest by Condition Class

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