City of Cambridge, Massachusetts
Urban Forest Management Plan

Scientific Analysis of Current Trends in Growth and Survival of Cambridge's Street Trees and Management Recommendations

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Table of Contents

Plain Language Summary

This report provides a scientific assessment of the survival and growth rates of public street trees in the City of Cambridge, MA. The purpose of this study is to provide information to land managers about the overall health of trees in the city. The results presented are provided as a practical tool to allow for comparisons in urban forest health, both within the city borders and with other cities. This study is designed as a roadmap to help improve management practices and identify which species are best suited to survive and grow in the city. As such, we assess how different biological, environmental, and socioeconomic/ community factors affect tree growth and survival. We provide analyses for all trees combined, as well as individual analyses for some of the most commonly planted species in the city, and include methodological and analytical details to allow for the study to be easily replicated. We divide the analyses into easy-to-navigate sections so that readers can find the topic they are most interested in, and provide “In a nutshell” summaries at the top of each section highlighting the most important results. We conclude with scientifically based management recommendations.

Scientific Background

Managing urban forests to optimize the ecosystem and community benefits that urban trees provide is a priority for many land managers, policy makers, and city residents. These benefits are numerous and are well documented elsewhere. In brief, trees are an attractive component of cityscapes, creating an inviting, pleasant environment for city-dwellers (*1*, *2*). This aesthetic appeal further translates to economic benefits, as homes with trees and other landscaping sell for more money (*3*), and commercial streetscapes containing trees receive more foot traffic and have increased sales compared to areas with no trees (*4*). Human wellbeing is also related to urban trees, as the health of urban residents is positively correlated with the number of street trees in their neighborhood (*5*, *6*). Finally, urban trees are an important component of city-level climate change adaptation (*7*, *8*). Not only do urban trees sequester carbon, but also by providing shade and through the effects of evapotranspiration, these trees help mitigate the urban heat island effect[1, 2].

Larger trees provide significantly more benefits than smaller trees (*3*, *9*). Yet, the potential benefits of urban trees are often not fully realized because of their short lifespans, ranging on average from 10 to 30 years (*10*, *11*). To maximize community benefits it is critical that newly planted trees survive until maturity and grow to their full potential. Urban trees need access to key resources such as water and nutrients to successfully grow and survive. But they are often challenged by multiple threats, including limited water availability due to drought and/or lack of permeable surface, compressed soil with low oxygen content and little space for root growth, low soil nutrient content with high salt concentrations, polluted air, various pests and pathogens, and physical damage by humans and storms (*10*, *12–18*). Certain tree species are better able to cope with some of these stressors than others, and because planting and maintaining urban trees is expensive (*19*), it is important to use information about the species and site characteristics to choose the tree for any specific location that has the best chance of survival.

Although the phrase “right tree, right place” is common in arboriculture, gathering the appropriate information to choose the right trees for a given location is not a trivial matter (*3*, *20*). The scientific knowledge base for making the best choices about which trees to plant, where to plant them, and how to best manage them, is only just emerging. To create an urban forest that is better able to withstand the threats of an urban environment, it is important to gather information about which factors most influence tree growth and survival in a given locale. A few studies of urban trees have taken place in Boston, MA (*10*, *21*), but, to our knowledge, this report is the first to look specifically at tree growth and survival in the City of Cambridge, MA, USA. Specifically, we assess how biological, environmental, and socioeconomic community factors influence tree survival and growth rates.

[1] The urban heat island effect is a generic term that applies to all cities. The built environment of cities traps more heat than natural environments, and, as a result, the temperature within urban areas is higher than the temperature of surrounding areas. The urban heat island effect refers to this temperature difference.
[2] Also see the 2015 Recommendation to the City Manager on Urban Heat Island Mitigation from the City of Cambridge’s Climate Protection Action Committee at http://www.cambridgema.gov/CDD/climateandenergy.

First, we provide a citywide overview looking at how the different factors influence growth and survival. We compare the growth and survival trends for young trees that were planted less than seven years ago to older trees that are more established and have a larger size. Then, we compare growth and survival at the species level, and provide species-specific analyses for 18 species that have sufficient data as young trees, older trees, or both. In the last section of this report, we provide recommendations for the future, addressing which species are most likely to survive to maturity in Cambridge, and what the focus of the next data collection efforts should be.

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Methodology

> **IN A NUTSHELL…**
> - This project was designed and led by scientists at Earthwatch Institute.
> - Measurements of tree growth and survival require multiple measurements over time.
> - The project was made possible by the City of Cambridge's public tree inventory, and by over 500 citizen scientists trained by Earthwatch staff who collectively spent thousands of hours collecting data for this project.

The City of Cambridge maintains a spatially explicit inventory of the more than 19,000 publicly owned trees in the City[3]. The initial inventory was started in 2005, and completed in 2011. The inventory contains information about the location, species identity, and size (diameter at breast height, or DBH) of each tree, as well as characteristics about the site where the tree is planted, such as if there are power line wires overhead. Approximately half of the trees in the inventory have a condition rating, which categorizes the overall health of the tree as "Dead", "Poor", "Fair", or "Good". The date of planting is also recorded for trees that were planted in 2007 or later. The inventory is continually updated when a tree is removed, planted, or re-measured. For a detailed description of the current state of Cambridge's urban forest refer to the ***Current State of the Urban Forest*** section of this Urban Forest Management Plan.

Between 2012 and 2015 Earthwatch Institute led an urban forestry citizen science program in the City of Cambridge. Earthwatch Institute is a global leader in "citizen science" — involving non-specialists, such as members of the public, families, educators, and students, in scientific research. Founded in 1973, Earthwatch Institute has been uniting citizen scientists with scientific research projects for over 40 years. Through the Earthwatch urban forestry program, over 500 citizen scientists visited and re-measured more than 4,000 trees in Cambridge's tree inventory. Citizen scientists visited each tree 1-3 times during the four-year period. Combining these measurements with the tree inventory data results in 2-4 measurement-time-points from which to assess tree survival and growth rates.

Professional scientists and expert citizen science leaders[4] designed the Earthwatch urban forestry program. They identified the goals of the research program, determined which trees to measure throughout the city, and trained citizen scientists in the data collection protocols. For each tree, the citizen scientists recorded the following data: species identification, tree diameter at breast height (DBH) to the nearest 0.1 inch, health condition of tree, presence or absence of flowers and fruits, presence or absence of power lines above the tree, presence or absence of sidewalk damage caused by the tree, and the date of measurement. Whenever possible, DBH was measured at 4.5' above the ground. In cases where the tree could not be accurately measured at 4.5' above the ground due to a bump or fork in the stem or any other imperfection, the citizen scientists recorded the height of measurement. In 2015, citizen

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[3] The current tree inventory is available at https://www.cambridgema.gov/theworks/ourservices/urbanforestry/treeinventory.

[4] The Earthwatch urban forestry program was designed and led by Gitte Venicx, Dr. Mark Chandler, Dr. Daniel Bebber, and Dr. Vanessa Boukili.

scientists also noted the presence or absence of tree well maintenance (*i.e.*, if the tree well had any evidence of care such as if the well was weeded or mulched, or if it contained a flowerbed or a fence around it), and whether or not the root flare was visible.

Prior to data collection, all citizen scientists underwent a 1.5-hour training session, where they were introduced to the importance of urban forests, the goals of the project, and the data collection methodology. During data collection, citizen scientists worked in groups of 2–4 people, and each group was equipped with a species identification binder, a forester's DBH tape (*i.e.*, *d*-tape), a map showing the designated trees to measure, and datasheets. The maps and datasheets had matching tree identification codes on them to reduce the possibility of recording data for the wrong tree.

Quality control analyses comparing the DBH measurements made by citizen scientists to measurements made by an expert confirm that the citizen scientist data are largely accurate. Earthwatch scientists completed two different types of quality control analyses — one in 2012 and another one from 2014 to 2015. In 2012, 70 randomly selected trees were measured both by citizen scientists and by an expert. For these 70 trees, the correlation between expert and citizen scientist measured DBH values was 98% (Pearson's $r = 0.98$), where 100% would mean that all of the values were the same. In 2014 and 2015, after the initial training session, each group of volunteers collected data on the same 1–3 trees that an expert had also measured. In total across these two years, citizen scientists made 296 measurements on 44 different trees. Only 15 of the 296 DBH measurements (5%) made by citizen scientists were large errors, differing from the expert measurement by 10% or more. Of the remaining 281 citizen scientist DBH measurements, the difference between the citizen scientist measurement and the expert measurement was 1.2% on average (± 0.09% standard error).

In addition to the tree measurements, we compiled spatially explicit environmental, and socioeconomic/ community variables from freely available databases at the city, state, and country level. See ***Table 1*** for a complete list of all of variables used in this study.

We use spatial datasets from the City of Cambridge and the State of Massachusetts to quantify environmental characteristics surrounding each tree. We use municipal level Geographic Information System (GIS) data to calculate the percent impervious surface surrounding each tree[5]. Impervious surface relates to impermeable features of the built environment, including asphalt, concrete, and rooftops. The percent impervious surface surrounding each tree will influence water and nutrient availability and soil compaction. We calculated the percent of impervious surface within a circular area with a 10-meter (10 m) radius surrounding each tree. Using a 10 m radius is somewhat arbitrary, but it is large enough to cover the entire root zone as well as the major rainfall catchment area for each tree.

[5] Impervious surface GIS layer can be acquired from www.cambridgema.gov.

In 2009 the State of Massachusetts collected airborne LiDar-derived digital elevation data at the spatial resolution of one meter (LiDar stands for Light Detection And Ranging)[6]. We used this LiDar data and the Spatial Analyst tool in the ArcGIS program to estimate annual growing season insolation[7] for each tree (megajoules per square meter; MJ/ m^2).

Socioeconomic conditions across the city were characterized by American Community Survey (ACS) data from the US Census Bureau[8]. For each of the 90 census block groups that are entirely or partially located in the City of Cambridge, we compiled data about the population density, housing density, owner occupancy rate, vacancy rate, the median household income, the percent of the civilian labor force who is unemployed, and the median year that housing was built. We use the socioeconomic factors as a proxy for the community capacity and commitment to tree care, and the median year that housing was built as a proxy for above and below ground infrastructure that may influence a tree's access to water and nutrients.

In addition, we used data from the City of Cambridge to quantify the number of publicly owned trees and tree wells in each census block, as well as the zoning district (residential, commercial, industrial, public space, or other) that each tree was located in. We also use these variables as proxies for commitment to tree care.

[6] 2009 LiDar data or the Greater Boston area can be acquired from www.mass.gov.
[7] Solar insolation was calculated for the time period spanning March 1st, 2012 to September 1st, 2012.
[8] ACS data can be acquired from www.census.gov/acs.

Table 1. Biological, environmental and socioeconomic variables used in this study.

Component Type	Data Source	Variable	Units	Variable Type
Biological	**City tree inventory and citizen scientist data**	Tree species	name	Categorical
		Initial tree size	inches	Continuous
		Final tree size	inches	Continuous
		Tree condition	rating	Categorical
		Measurement date	date	Discrete
		Planting season[§]	date range	Discrete
		Root flare visible	yes or no	Discrete
Environmental	**City tree inventory and citizen scientist data**	Wires overhead	yes or no	Discrete
		Sidewalk damage	yes or no	Discrete
		Tree well maintenance	yes or no	Discrete
	Cambridge GIS Database[$]	Impervious surface within 10 m radius of tree	proportion	Continuous
	Massachusetts 2009 LiDar data[#]	Solar insolation	MJ m^{-2}	Continuous
Socioeconomic/ Community	**US Census Data: 2009-2013 ACS (census block group level)[^]**	Population density	# people ha^{-1}	Discrete
		Housing density	# housing units ha^{-1}	Discrete
		Owner occupancy rate	percent	Continuous
		Vacancy rate	percent	Continuous
		Median household income	dollars	Continuous
		Population unemployed	percent of civilian labor force	Continuous
		Median year housing built	year	Discrete
	Cambridge GIS Database[$$]	Public trees and tree wells in each census block	count	Discrete
		Zoning, residential areas	yes or no	Discrete
		Zoning, commercial areas	yes or no	Discrete
		Zoning, industrial areas	yes or no	Discrete
		Zoning, open space areas	yes or no	Discrete
		Zoning, other areas	yes or no	Discrete

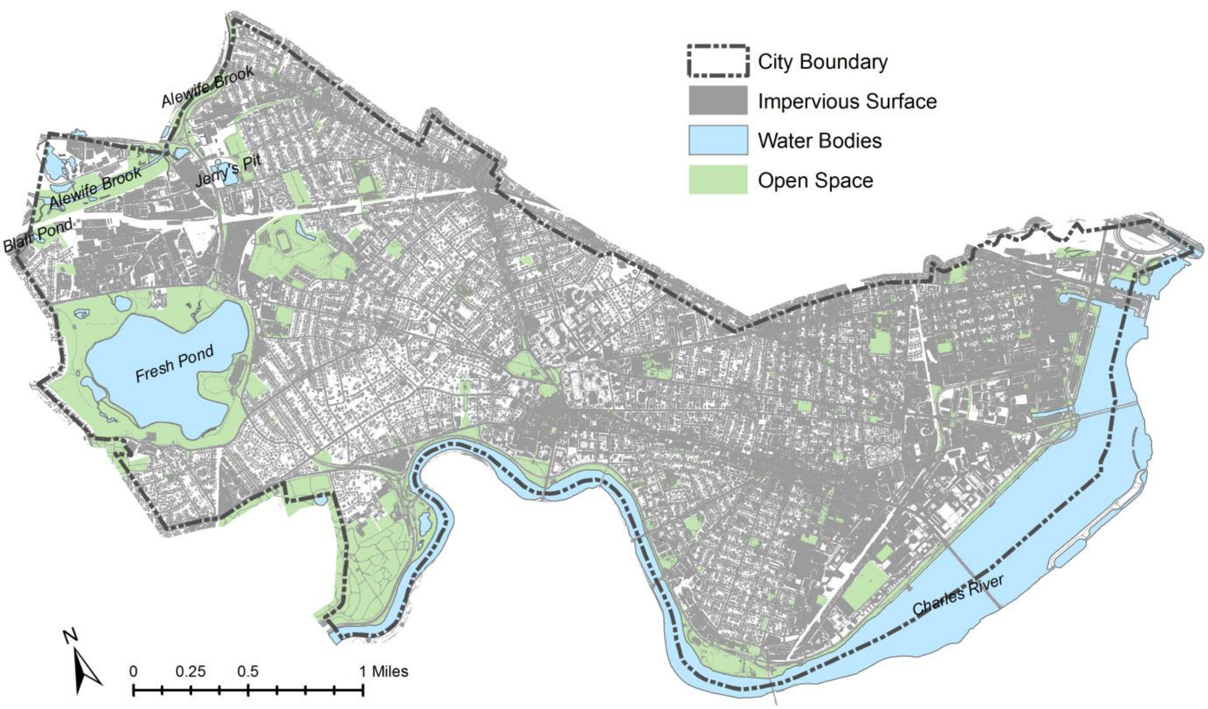
[§]Only applies to trees planted in 2007 or after.
[$]Data from: www.cambridgema.gov/GIS/gisdatadictionary/Environmental
[$$]Data from: www.cambridgema.gov/GIS/gisdatadictionary/CDD. Land use categories were condensed into five zoning categories. See ***Appendix A*** for details.
[#]Data from: www.mass.gov.
[^]Data from: www.census.gov.

Citywide trends in independent variables

> **IN A NUTSHELL…**
> - Environmental and socioeconomic conditions vary across the City of Cambridge.
> - These variables may influence tree growth and survival, either directly or indirectly.
> - By identifying which of these variables are most important for urban tree growth and survival we can figure out how to create a healthier, more resilient urban forest.

The City of Cambridge spans 7.13 square miles, 4.01 square miles of which are covered in impervious surface (56.2%). Impervious surface is comprised of structures and materials that are impenetrable by water, such as buildings, structures, and paved surfaces (road, sidewalk, parking lots, driveways). The extent of impervious surface in the City is shown in ***Map 1***. By zooming into a small section of the city, the impervious surface area becomes a united patchwork of buildings, roads, driveways, and paths (***Map 2***). Rectangular openings in the sidewalk show the locations of street tree wells.

Map 1. Impervious surface area across the City of Cambridge.



Map 2. Zoomed in view of impervious surface extent and tree well locations.

The areas in white, green, and orange are pervious (permeable) surface, whereas the areas in grey are impervious (impermeable) surface.

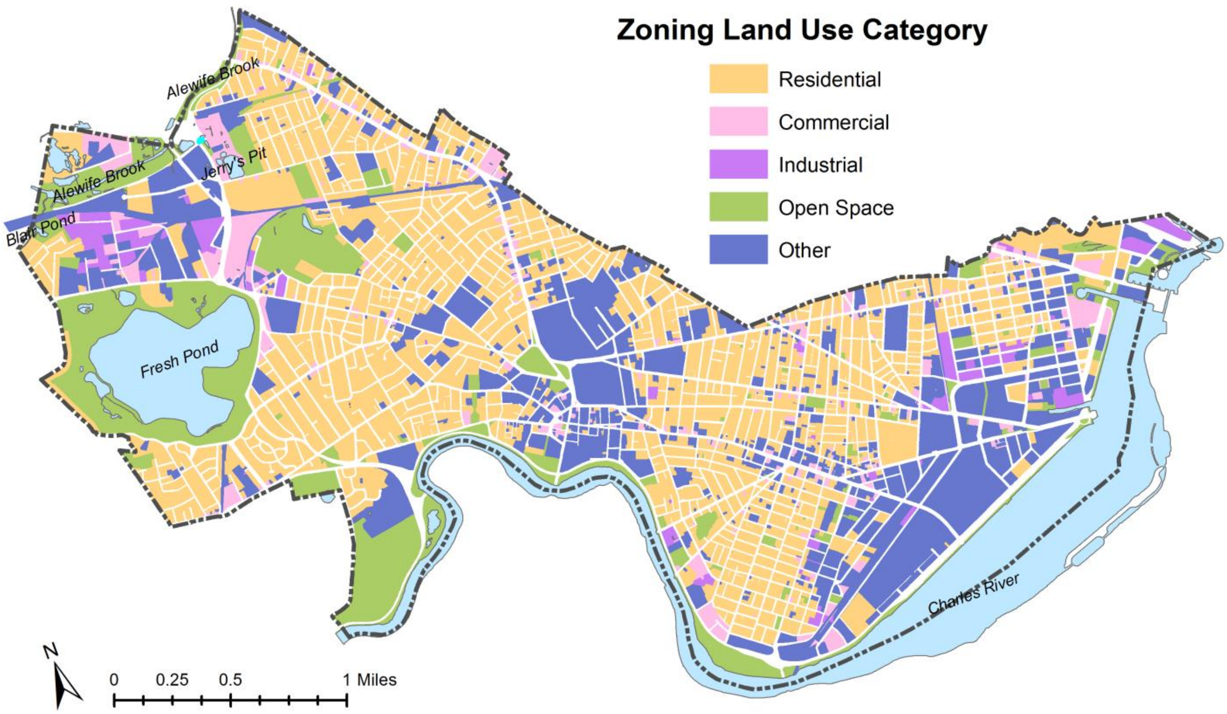
We distilled the zoning categories throughout the City into "Residential", "Commercial", "Industrial", "Open Space", and "Other". ***Map 3*** shows the distribution of these different zoning categories throughout the city. More detailed Zoning Ordinance maps can be found online at the City of Cambridge website[9]. See ***Appendix A*** for details about how the zoning categories were derived.

There are 90 census blocks across the 13 different neighborhoods in the City. Note that the neighborhood called "The Port" used to be called "Area Four", and the neighbhorhood called "West Cambridge" used to be called "Neighborhood 10".

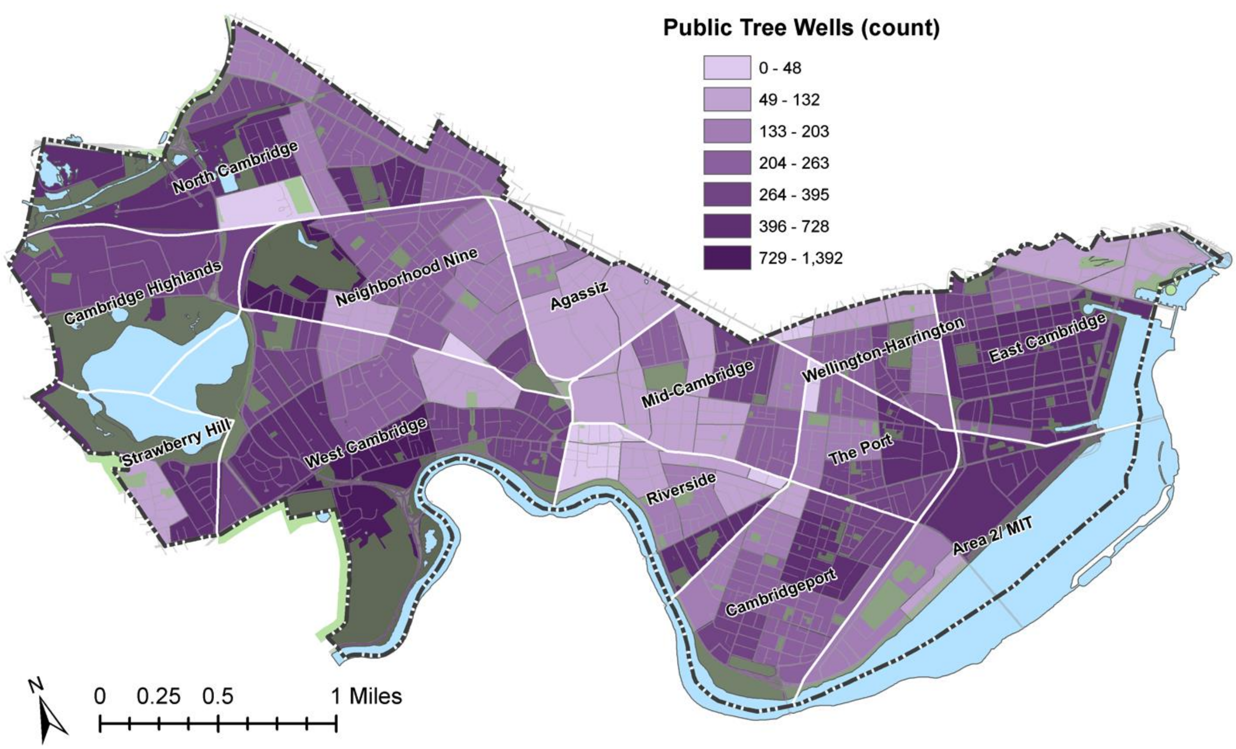
The number of public tree wells in each census block ranges from 0 to 1,392 tree wells (***Map 4***). Portions of West Cambridge and Neighborhood Nine have the highest density of public tree wells, in the census blocks where Mount Auburn Cemetery and Danehy Park are located. Parts of North Cambridge, East Cambridge and Area 2/ MIT also have high numbers of public tree wells. Selected census blocks in the Agassiz, Riverside, Mid-Cambridge, and North Cambridge neighborhoods have the fewest number of public tree wells.

[9] Zoning Maps can be acquired from https://www.cambridgema.gov/CDD/zoninganddevelopment/Zoning/Maps.

Map 3. Zoning land use categories across the City.



Map 4. Public tree wells by census block.

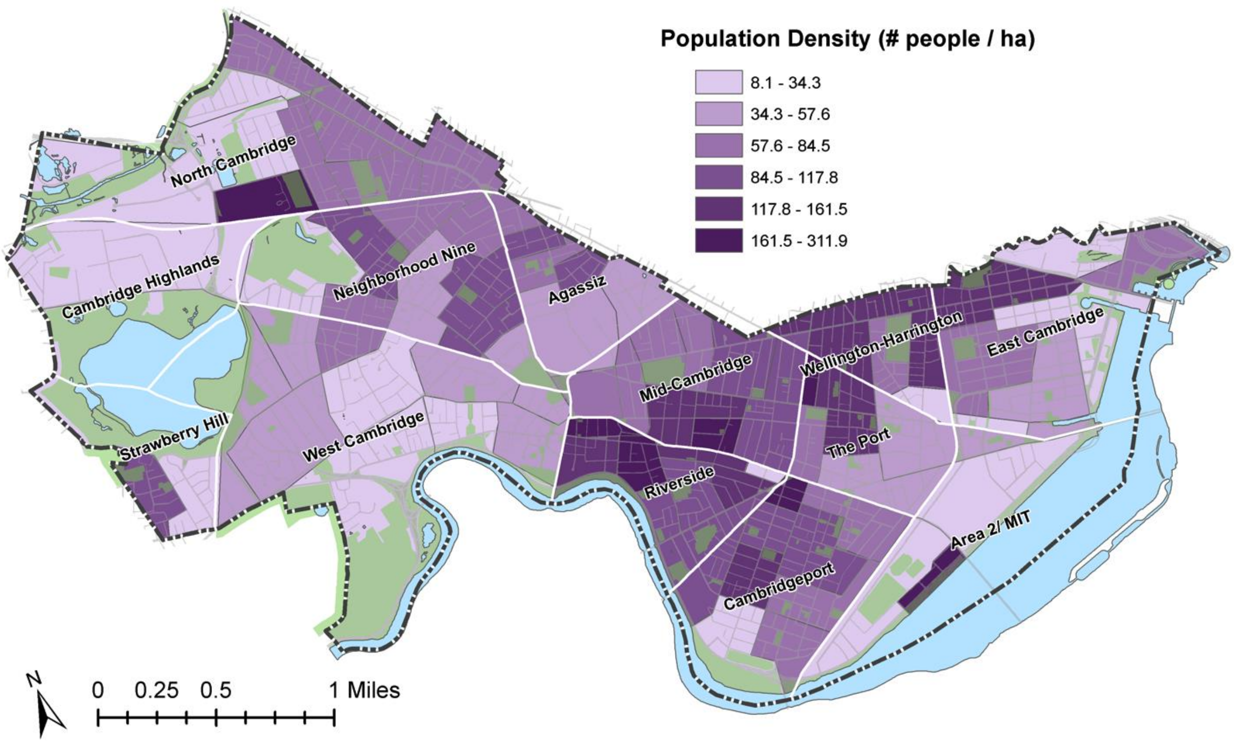


The variation in socioeconomic conditions among the different census blocks across the City is shown in ***Maps 5–11***.

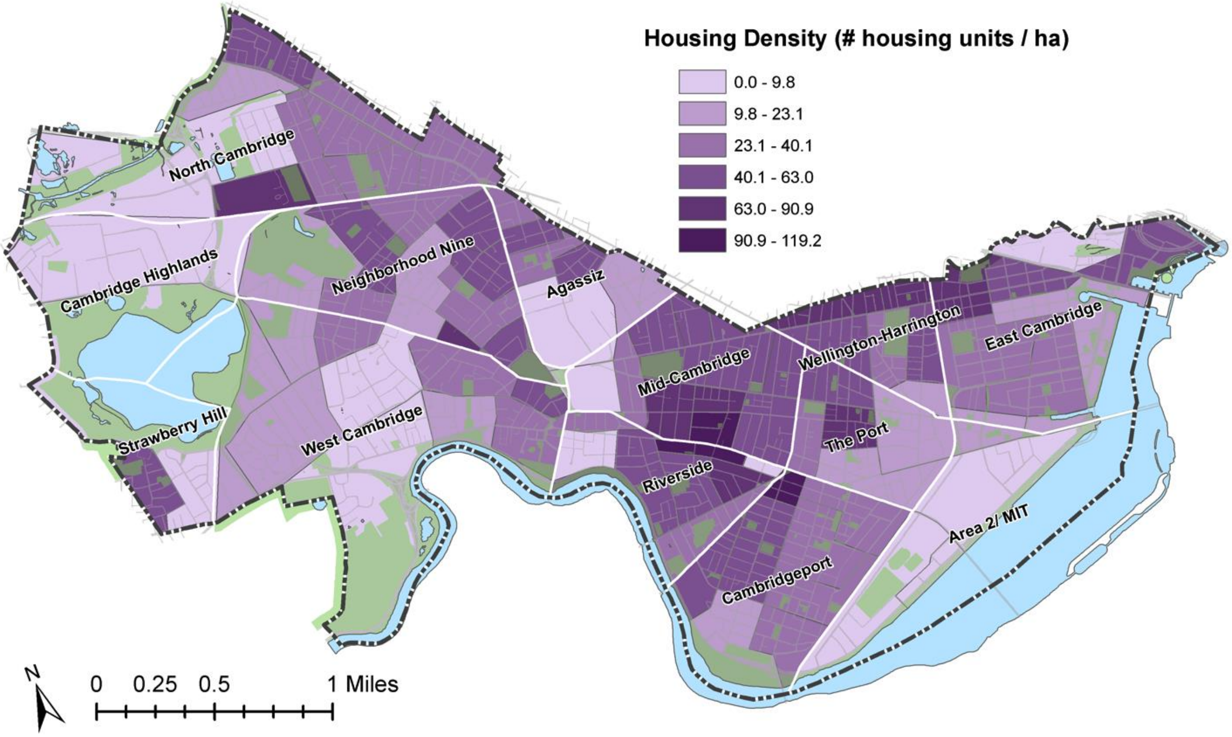
The population density of residents across the city ranges from 8.1 to 311.9 people per hectare (***Map 5***). The least densely populated areas primarily occur in Area2 / MIT, West Cambridge, Cambridge Highlands, and North Cambridge. The most densely populated areas occur in parts of North Cambridge, Riverside, Mid-Cambridge, Cambridgeport, The Port, and Area 2/ MIT.

Housing density across the City ranges from 0 to 119.2 housing units per hectare (***Map 6***). In general, areas with high population densities also have high housing densities, and vice versa. However, the most densely populated area of The Port has only a mid-level housing density. Also, some of the census blocks near Harvard Square in the Mid-Cambridge and Riverside neighborhoods have higher population densities than expected based on the housing density.

Map 5. Population density by census block.

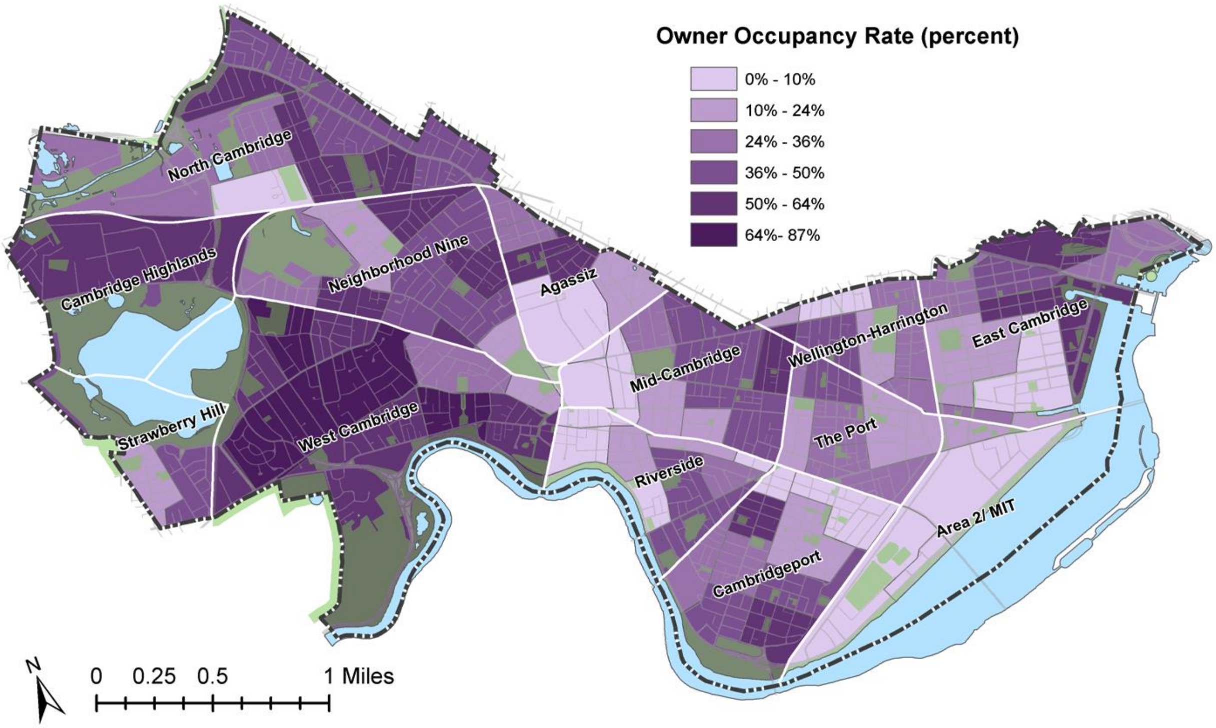


Map 6. Housing density by census block.

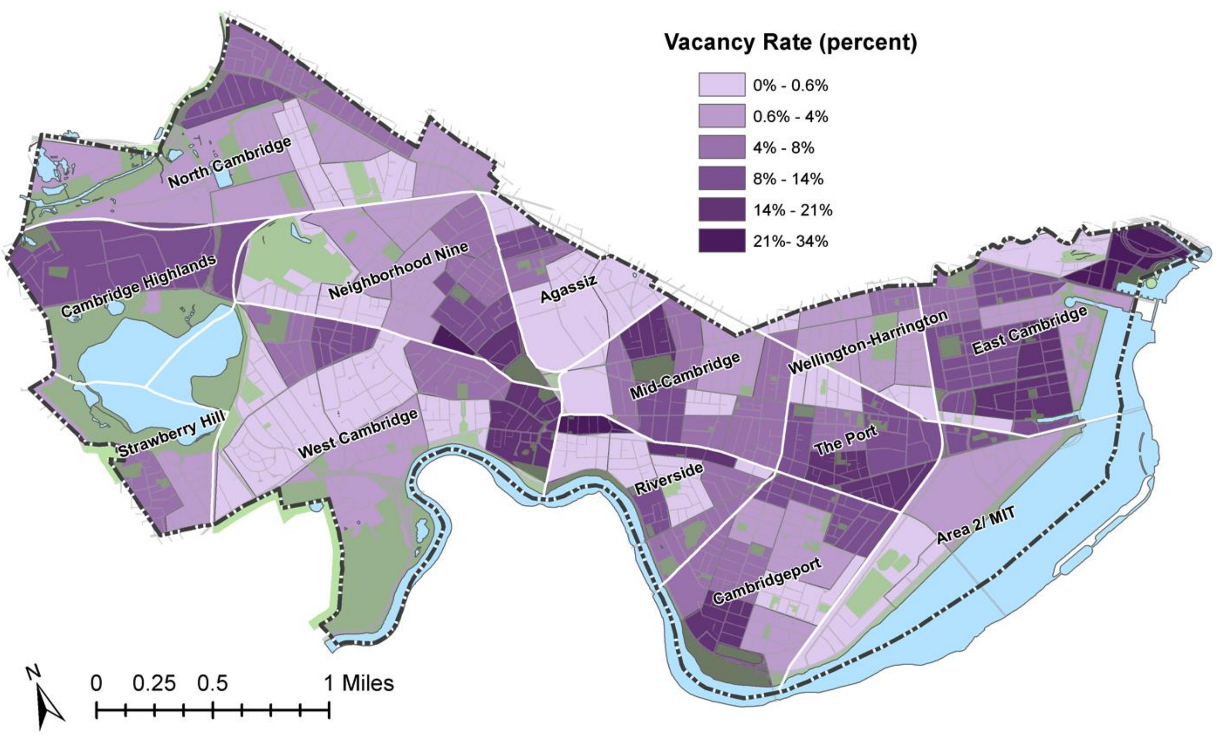


The residential owner occupancy rate varies from 0% to 87% (***Map 7***), with the highest owner occupancy levels occuring primarily in West Cambridge, Cambridge Highlands, North Cambridge, and the eastern side of East Cambridge. The residential vacany rate ranges from 0% to 34% across the City (***Map 8***), and is highest in sections of East Cambridge, Riverside, and Neighbhorhood Nine.

Map 7. Owner occupancy rate by census block.



Map 8. Vacancy rate by census block.



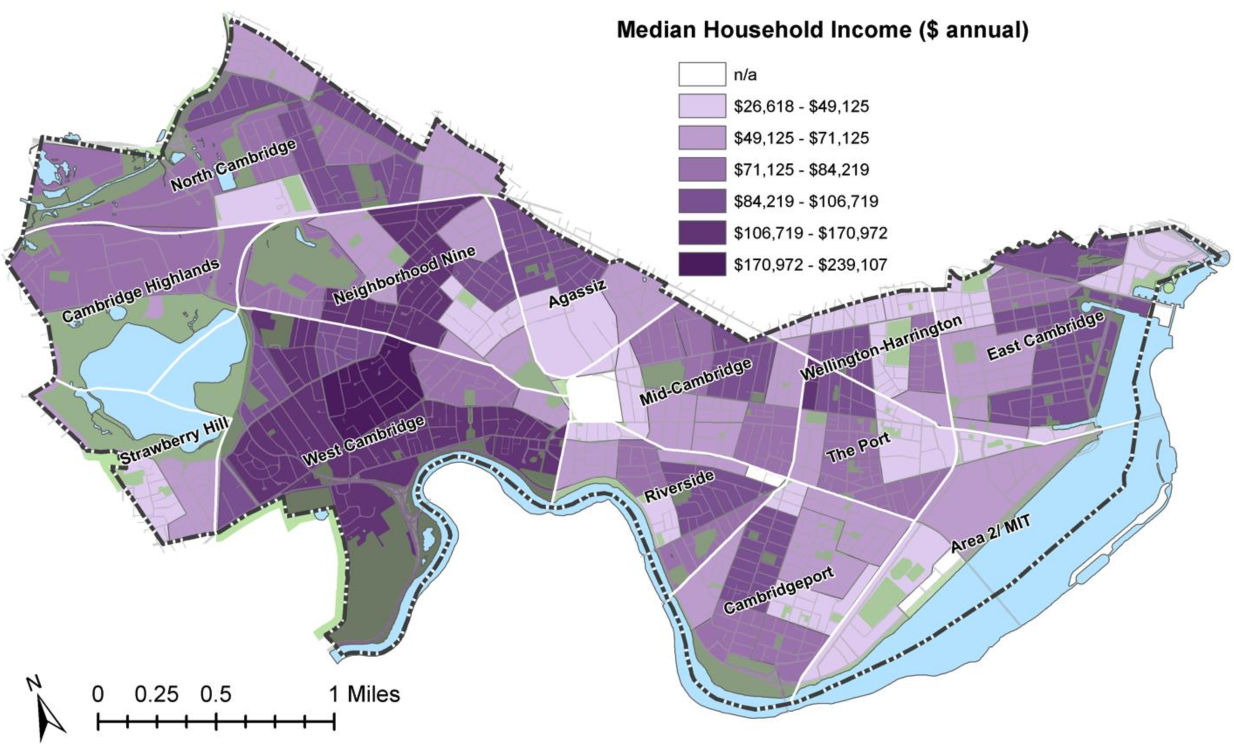
Median household income ranges from $26,618 to $239,107 throughout the City (***Map 9***). The census blocks with the highest median household incomes are found in West Cambridge and Neighborhood Nine.

Across the census blocks throughout the City, the range in the percentage of the civilian labor force that is unemployed ranges from 0 to 83% (***Map 10***). Across the City, the highest percentage of the population that is unemployed is found in one census block located in the eastern corner of the Riverside neighborhood. Most of West Cambridge and parts of North Cambridge, Neighborhood Nine, Agassiz, North Cambridge, Riverside and Cambridgeport have the lowest percentages of the population that is unemployed.

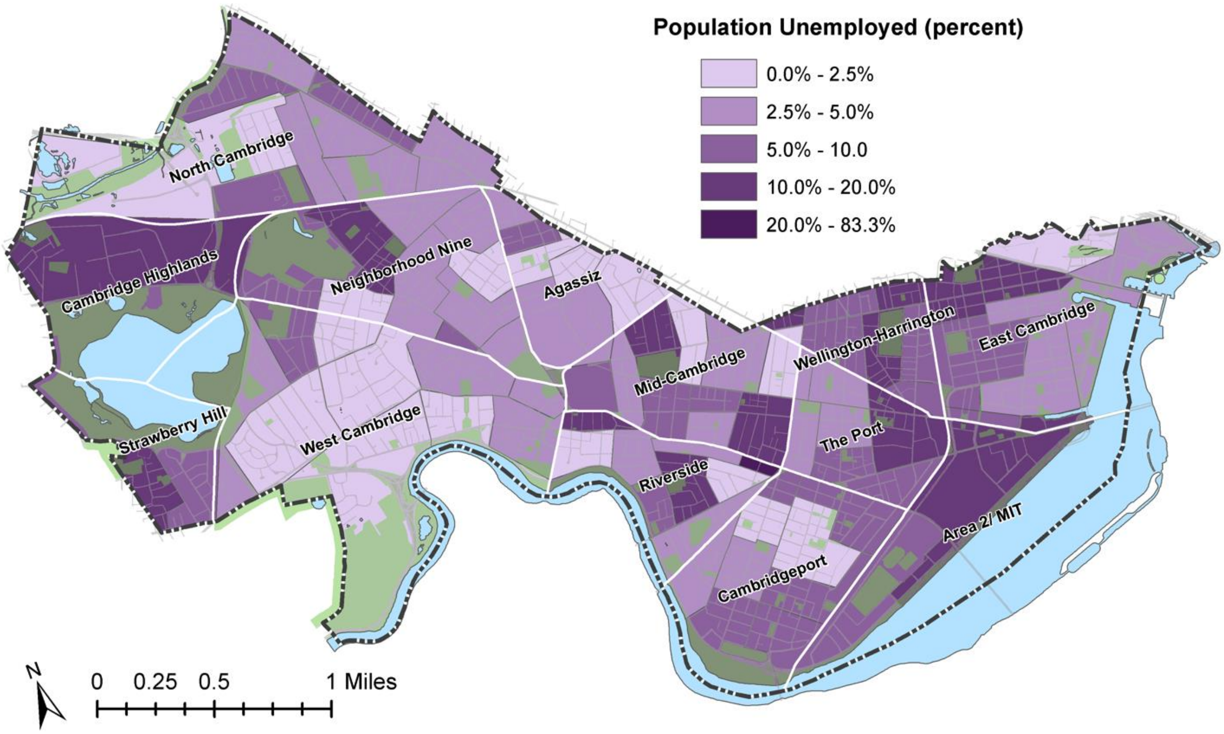
The median year that housing was built spans from 1939 to 2004, but majority of houses in the City of Cambridge were built between 1939 and 1945 (***Map 11***).

No data on median household income or median year housing built were available for three census blocks.

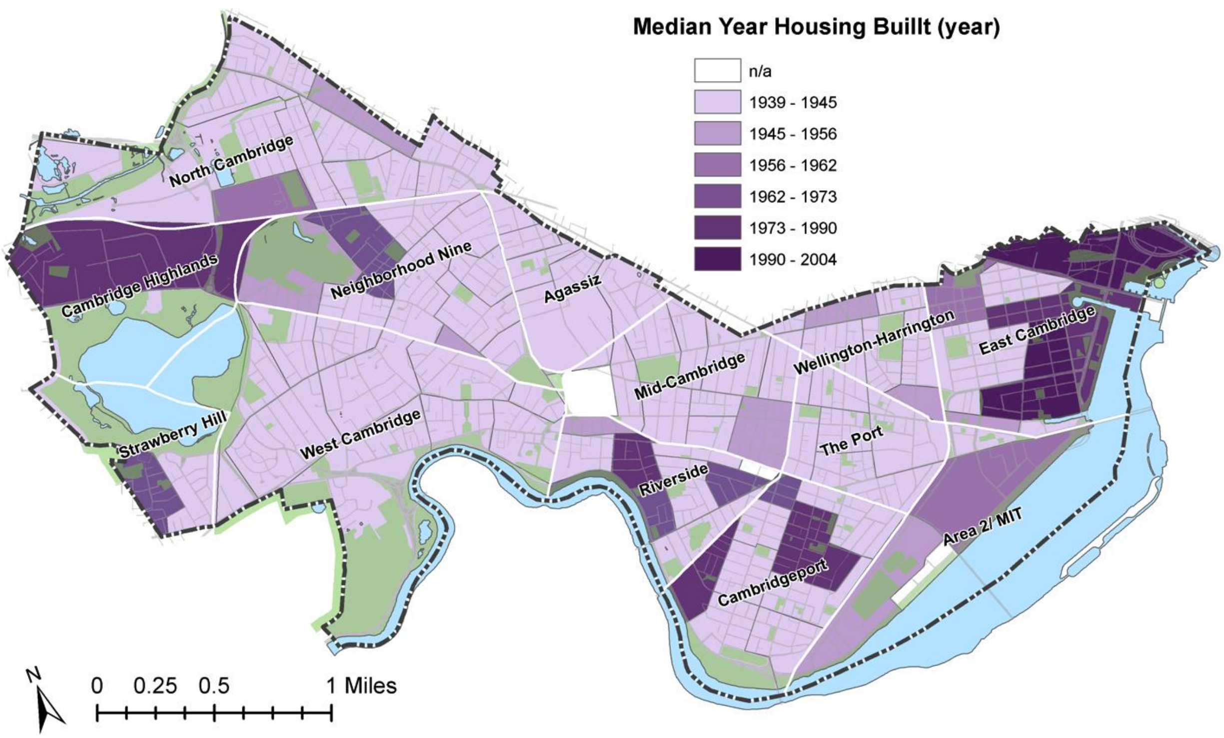
Map 9. Median household income by census block.



Map 10. Population unemployed (civilian labor force) by census block.



Map 11. Median year housing built by census block.



Overview of survival rates for young and old street trees

Annual Survival, Mean Life Expectancy, and Population Half Life

IN A NUTSHELL…

- The mean estimated annual survival rate is 96.7% per year for young trees and 90.8% for older trees.
- The mean life expectancy for young trees is ~30 years.
- Young trees survive better when they experience lower light levels, and in residential and commercial zones. They also survive better in areas with fewer public tree wells and lower median income levels.
- Old trees survive better when they are surrounded by less impervious surface, in areas with more public tree wells, and in residential and commercial zones. Various socioeconomic conditions of the surrounding neighborhood also influence their survival.

We use a standard life table approach to assess annual survival of the street tree population in the City of Cambridge. This life table approach compares the number of trees that were alive at the beginning of the study to the number of those trees that were still alive at the end of the study. If the number of trees alive at the end of the study is lower than the number of trees that were alive at the beginning of the study, that means that some of the trees died, either from natural causes or they were removed because they presented a hazard to the public. The difference in the number of trees is standardized by the amount of time, in years, that the trees were studied, thus providing an estimate of annual survival. We calculated annual survival estimates using the following equation:

$$\text{Annual Survival} = \left(\frac{\text{Number of trees at time } t}{\text{Number of trees at time zero}}\right)^{1/t},$$

where *t* is the amount of time, in years, between the first recorded measurement and the last recorded measurement.

Annual survival rate was calculated separately for young trees (planted in 2007 or later that have a known plant date) and old trees (trees established before 2007) for each year of time. The amount of time between the first and final measurement ranges from 1 to 7 years for young trees, and 1 to 10 years for old trees. We calculated annual survival rates separately for each cohort of trees (*i.e.*, trees where the amount of time between the first and final year of measurement was 1 year, 2 years, 3 years, *etc.*), and then calculated the average annual survival across all cohorts.

Young trees are trees that were planted between 2007 and 2015. Young trees have a recorded date of planting in the inventory, and at the time of planting ranged in size from 1.0 inch to 4.1 inches in diameter (DBH). The time between the first and last recorded measurements for the 1,927 young trees in our dataset spans from 1 to 7 years.

Old trees are trees in the inventory that range in size from 4.2 to 45.0 inches DBH, and do not have a recorded date of planting. They were planted sometime prior to 2007. For the 1,571 old trees in our dataset, the time between the first and last measurement spans from 1 to 10 years.

It is important to note that the annual survival rate estimates have different meanings for the young and old trees in our dataset. For the young trees, annual survival rate is calculated from the time of planting, such that the survival reflects actual tree age (or, more specifically, the amount time the trees have been in the ground at their current location, since their age at the time of planting in the City is unknown). For old trees, annual survival rate reflects the survival since the time they first entered the database, since there is no record of what year they were planted in the ground.

On average, the annual survival rate for young trees is 96.7%, and the annual survival rate for old trees is 90.8% (***Table 2***). However, the 95% confidence intervals[10] of the annual survival rates for young and old trees overlap, meaning that the difference in the annual survival rate estimates of young and old trees is not significant. Compared to other published studies, the mean annual survival rate estimate for the young trees in the City of Cambridge is relatively high, whereas the estimate for old trees is relatively low. In a meta-analysis of 16 urban forest studies[11], the estimated annual survival rates ranged from 0.4–99.7%, with a median of 95%. Seventy-five percent of the studies reported an annual survival rate of more than 91.0%.

Although the annual survival rates for young and old trees in the City of Cambridge are not significantly different, we continue to keep the survival analyses separate for young and old trees throughout the remainder of this document. We do this for various reasons. Most importantly, as described above, the annual survival rate estimates have different meanings for young and old trees. Also, although overall survival may not differ for young and old trees, certain species may still be more vulnerable in younger or older stages, and the biological, environmental, and socioeconomic conditions may influence trees in different life stages in different ways.

We used the average estimated annual survival estimates to calculate life expectancy rates[12]. The life expectancy for young trees in the City of Cambridge is 29.5 years, whereas the life expectancy for old trees is only 10.4 years beyond the first date of measurement. Based on the young tree life expectancy rate, a tree that is planted in Cambridge is expected to live approximately 30 years. The reduced life expectancy for old trees makes sense, as these trees have already lived in the city for at least 8 years, since they were planted sometime prior to 2007. Assuming that the mortality rate is constant throughout a tree's lifetime, the difference in life expectancy values for young and old trees would suggest that many of the old trees were planted over 20 years ago.

[10] 95% confidence intervals of the mean were calculated based on a *t*-distribution with six degrees of freedom for the young trees data set, and a *t*-distribution with nine degrees of freedom for the old trees data set. The degrees of freedom are calculated as *n-1*, where *n* is the number of years for which annual survival was calculated.
[11] Roman & Scatena 2011 (see citation #11 in the ***References*** section). The 16 cities in the meta-analysis were located in CA, IA, IL, MA, NY, OH, PA, MD, WI, Northeastern US, Belgium, China, and England.
[12] As calculated in Roman & Scatena 2011 (citation #11), mean life expectancy $= -1/\ln(\text{annual survival rate})$.

We also used the average annual survival estimates to calculate the population half-life, or the estimated time in which half of the trees in the population are dead[13]. Because of the asymptotic relationship between annual mortality rate (the inverse of survival) and mean life expectancy, mean life expectancy rates can reach hundreds of years or more when annual survival rates are very low. Thus, for practical applications, population half-life may be more useful because it estimates the value for the population as a whole, and is therefore less influenced by outliers. Based on the estimated annual survival rates, the population half-life of young trees is 20.4 years, and the population half-life of old trees is 7.2 years beyond the first date of measurement.

Table 2. Annual survival estimates for young trees and old trees.
The annual survival estimate for old trees is lower than for young trees, but difference is not significant because the 95% confidence interval (CI) estimates overlap. Mean life expectancy and population half-life values are based on annual survival rate estimates. The 95% CIs demonstrate that there is a high level of uncertainty in our estimates.

Dataset	Range initial DBH (inches)	Estimated annual survival (mean ± standard error)	95% CI for annual survival estimate	Mean Life Expectancy (# years) [95% CI]	Population Half-Life (# years) [95% CI]
Young Trees	1.0–4.1	96.7% ± 1.2%	93.8% – 99.5%	29.5 [15.6, >100]	20.4 [10.8, >100]
Old Trees	4.2–45.0	90.8% ± 5.2%	79.0% – 102.7%	10.4 [4.3, >100]	7.2 [2.9, >100]

Norway maples comprise about one-third of the old trees in our survival study (499 trees out of 1,571), and this species has the lowest survival rate of all the species in our study (see ***Table 6*** in ***Species-specific trends in survival and growth*** section, below). Norway Maple has not been planted in Cambridge since it was placed on the Massachusetts Prohibited Plant List on January 1st, 2009[14]. To test if the low survival rates of Norway Maple trees are driving the lower annual survival estimates of all old trees, we re-estimated the annual survival rate of old trees without Norway Maples. The annual survival estimate for old trees increased slightly when Norway Maples were excluded, but the results were not significantly different. Excluding Norway Maples, the estimated annual survival rate of old trees was 91.7% ± 5.0% (95% CI: 80.4–102.9%), with a mean life expectancy of 11.5 years beyond the date of last measurement (95% CI: 3.9 to >100 years), and a population half-life of 8.0 years (95% CI: 2.7 to >100 years).

For young trees, we estimated survival rate for the different planting seasons. The ‘spring’ planting season refers to trees planted between March 1st and May 31st, the ‘summer’ planting season refers to trees planted between June 1st and August 31st, and the ‘fall’ planting season refers to trees planted between September 1st and November 30th, for any calendar year. Our results show that planting season does not have a significant effect on the annual survival rate of young trees (ANOVA; df = 2, 18, F = 0.01, $p = 0.995$, ***Table 3***).

[13] As calculated in Roman & Scatena 2011 (citation #11), population half-life = $\ln(0.5)/\ln(\text{annual survival rate})$.
[14] http://www.mass.gov/eea/agencies/agr/farm-products/plants/massachusetts-prohibited-plant-list.html.

Table 3. Annual survival estimates for young trees by planting season.
Estimates do not differ significantly among planting seasons.

Planting Season	Number of trees	Range initial DBH (inches)	Estimated annual survival (mean ± standard error) %
Spring	633	1.0–4.0	96.6 ± 1.3
Summer	303	1.0–4.0	96.8 ± 1.2
Fall	991	1.0–4.1	96.8 ± 1.2

Impact of Biological, Environmental, and Socioeconomic/ Community Factors on Survival

To assess the impact of the various biological, environmental, and socioeconomic/ community variables on survival, we used Cox Proportional Hazards models. This type of model assesses the risk of mortality for different levels of each covariate (variable). The output is an exponentiated hazard ratio, which is scaled relative to one. The exponentiated hazard ratio coefficients are interpreted as multiplicative effects of each covariate on the risk of dying. Values higher than one mean that the variable increases the risk of death, and values lower than one mean that the variable lowers the risk of death. A 95% confidence interval that contains the value of one means that there is not enough statistical evidence to suggest that the covariate affects survival.

We used Cox Proportional Hazards models for interval-censored data, because our data is both left- and right-censored. Our data are left-censored because the initial time at risk is unknown, as we do not know how old the young trees are, and for old trees we do not know when they were planted in the ground. Our data is right-censored because the study ended before we could account for the time to death for all trees.

Separately for young and old trees, we ran multivariate Cox Proportional Hazards models, which included all of the covariates of interest in our study. Performing an analysis that includes all covariates allows us to determine the influence of each covariate while holding all other covariates constant. Prior to running these analyses we standardized the values of each covariate to have a mean of 0 and a standard deviation of 1 across all species. In this way, the model outputs are directly comparable across covariates. However, because each covariate was standardized, the exponentiated coefficients cannot be directly translated into the original units of the covariate. Instead, interpret the results for each covariate in relation to the other covariates. The higher the value is above one, the more that covariate increases the risk of dying. The lower the value is compared to one (*i.e.*, closer the value is to zero), the more that covariate decreases the risk of dying.

RESULTS AND INTERPRETATION

Five out of fourteen covariates significantly influenced the risk of mortality for the young trees (***Figure 1a***):

1. *Young trees exposed to higher light conditions (Solar Insolation) were more likely to die*. Plants in higher light conditions have higher photosynthetic rates. When plants

photosynthesize, they are also loosing water through transpiration. If a tree cannot take up a sufficient amount of water through its roots to keep up with the water loss from its leaves, then the tree will become water-stressed. Water-stress causes embolisms in the xylem and can eventually lead to death. The fact that young trees are more likely to die in higher light conditions suggests that sunlight is not a limiting factor for these urban trees, but water availability is.

2. *Young trees in census blocks with <u>higher numbers of public trees and tree wells were more likely to die</u>.* This pattern was unexpected, but could result from a reduced commitment to tree care in areas that have many trees. When there are many trees, it may be difficult to maintain tree care for all of them.
3. *Young trees in areas with <u>higher median income levels were more likely to die</u>*. This result was also surprising, and contradicts the results of a study performed on street trees in Indianapolis[15]. The highest median income levels in the City of Cambridge are found in parts of West Cambridge and Neighborhood Nine (see ***Map 9***). West Cambridge has been undergoing high levels of construction for the last few years due to the Huron B and Concord Avenue reconstructions that are part of the Alewife sewer separation project. Thus, median income levels in our study are somewhat confounded with construction projects, which may explain why fewer young trees survive in areas with higher median income levels.
4. *Young trees in <u>residential</u> or <u>commercial zones were less likely to die</u> compared to young trees in industrial, open space or other zones*. The “other” category includes offices, educational areas, government buildings, health care facilities, and transportation areas (see ***Appendix A***). Although the data set used in this analysis included a higher number of trees Residential zones compared to any other zone (1,363 trees in Residential, 112 trees in Commercial, 24 trees in Industrial, 14 trees in Open Space, and 389 trees in Other category), this has little effect on the analysis. One possibility for the higher survival rates in Residential and Commercial zones in that there is a higher commitment to tree care in these zones compared the other zones. Another possibility is that trees in Industrial and Other zones experience more damage than trees in Residential and Commercial zones. Damage to the trunk or roots can impair a tree’s ability to uptake water and nutrients, and also leaves the tree vulnerable to disease and infection.

Nine out of fifteen covariates significantly influenced the risk of mortality for the older trees (***Figure 1b***).

1. *Older trees with a <u>higher proportion of impervious surface within 10 m</u> of the trunk <u>were more likely to die</u>*. Impervious surface increases soil compaction and reduces water and nutrient availability. Root damage or a lack of water or nutrients can limit a tree’s ability to survive. Moreover, as a tree become larger, its root zone expands. Because the percent of impervious surface surrounding the trees affects the survival of old trees but not young trees, this suggests that the negative impacts of impervious surface become increasingly detrimental with tree age (or size).

[15] Vogt et al. 2015 (see citation #19 in the ***References*** section).

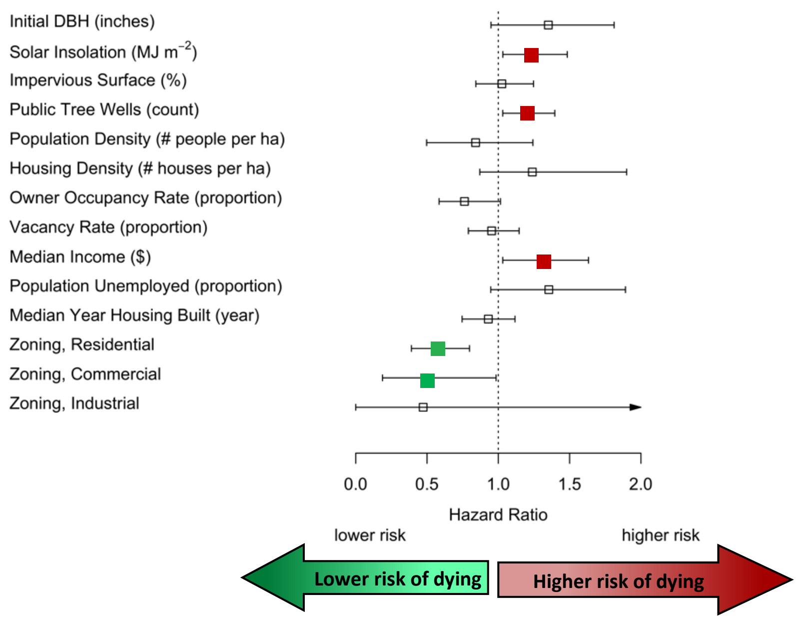
2. *Older trees in census blocks with higher numbers of public trees and tree wells were less likely to die.* This pattern is the opposite of what was found for young trees, and suggests that the proportional commitment to tree care does not impact older trees as much as it does for young trees. Older trees have better established root zones and canopies than young trees, and thus may be less dependent regular maintenance. Another explanation for this pattern is that areas that have more public trees may simply be more amenable areas for trees, once they are established.
3. *Older trees in areas with higher population densities were less likely to die, but older trees in census blocks with higher housing densities were more likely to die.* This pattern is surprising because population density and housing density are highly correlated ($r = 0.97$). However, recall that this analysis assesses the influence of each covariate while holding all other covariates constant. Thus, together these results suggest that for trees inhabiting census blocks with similar population densities, those in census blocks with higher housing densities are more likely to die. In order to fit the same number of people in the same amount of space, the combined building footprint of an area with a higher housing density would be much larger than the footprint of an area with a lower housing density. A higher building footprint could result in less room for the trees to grow, purportedly leading to more stressful growing conditions and thus lower survival. Higher housing density may also be correlated with the number of cars in an area. A higher number of cars in area may increase the likelihood of stem damage to the trunks, and may also influence air quality.
4. *Older trees in areas with higher owner occupancy rate were less likely to die.* Owners are more likely to have a vested interest in their neighborhood, and spend more time and effort maintaining the trees nearby. There is also a good chance that, compared to renters, a higher proportion of owners know what kinds of maintenance they can provide for public trees (such as water and mulch), and know to contact the City when any other type of tree maintenance is needed. Thus, the higher survival rate of older trees in areas with higher owner occupancy rates suggests that older trees do better when the commitment to tree care is higher. However, this somewhat contradicts with one of our explanations for the public tree well result (#2, above). It is also possible that survival is higher in areas with higher owner occupancy rates because trees in these areas experience less damage to trunks and roots.
5. *Older trees in areas with higher percentages of the population that are unemployed were less likely to die.* We are unsure how to interpret this result, but it is possible that people who are unemployed are home more often, and thus provide more care for the public trees in their neighborhood. Or perhaps the trees in areas with higher unemployment rates experience less damage to trunks and roots.
6. *Older trees in areas with higher median income levels were more likely to die.* This pattern was also found in young trees, and may result from the high levels of construction in the areas of the City with the higher median levels.
7. *Older trees in residential and commercial zones were less likely to die compared to older trees in other zones.* This pattern was also found in young trees, and suggests that the commitment to tree care is higher in Residential and Commercial zones compared to other zones, and/or trees in these zones experience less damage to roots and trunks.

EARTHWATCH INSTITUTE

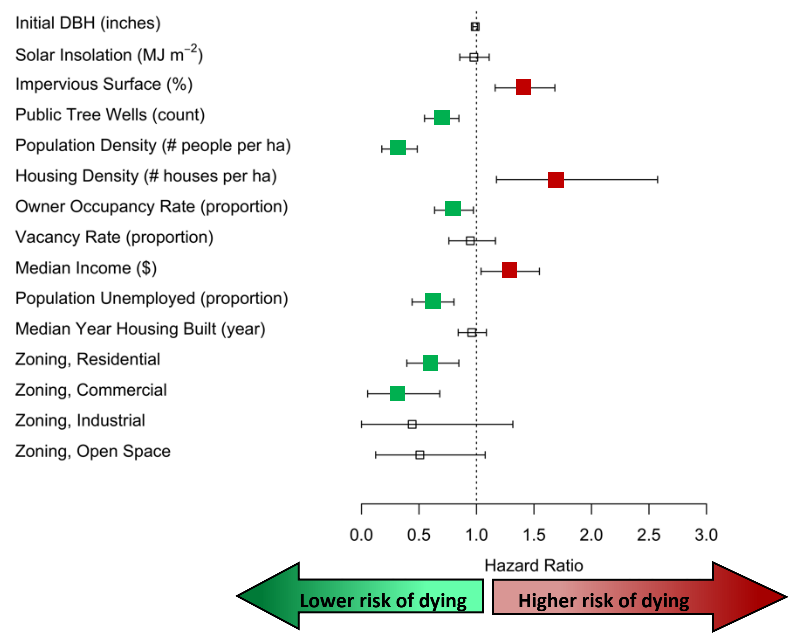
Figure 1. The influence of biological, environmental, and socioeconomic factors on the risk of tree death for a) young trees and b) old trees in the City of Cambridge.

Figures show Cox Proportional Hazards model results. In each figure, squares that are to the right of the vertical line show that higher values of that covariate increase the risk of a tree dying, whereas squares located to the left of the vertical line show that higher values of that covariate reduce the risk of a tree dying. The error bars are 95% confidence intervals. Squares whose error bars overlap the vertical line (hollow squares) are not significant. For example, although the risk of a young tree dying tends to be higher for trees with a larger initial tree size (Initial DBH), the pattern is not significant. Squares whose error bars do not overlap the vertical line (filled squares) significantly influence the risk of a tree dying. For ease of interpretation, covariates that significantly increase a tree's risk of dying are colored in **red**, and covariates that significantly decrease a tree's risk of dying are colored in **green.** For example, young trees that experience higher light conditions (Solar Insolation) have a significantly higher risk of dying than trees in lower light conditions, and young trees located in Residential zones have significantly lower risk of dying than trees located in other zones.

a) Young trees



b) Old trees



Overview of growth rates for young and old street trees

IN A NUTSHELL…

- Young trees grow faster than old trees.
- For both young and old trees, growth rate varied significantly by species.
- Among the young trees, those with larger diameters grow faster, but the opposite is true for old trees.
- Young trees planted in the spring grow faster than young trees planted in the summer or fall.
- Young and old trees in residential areas grow faster than trees in other zones.
- Old trees in areas with newer residential construction or lower vacancy rates grow faster.

Relative Growth Rate

We calculated relative growth rate for each surviving tree. Relative tree growth rate is calculated based on the tree diameter, or Diameter at Breast Height (DBH) measured at two different time points. The equation to calculate relative growth rate is as follows:

$$\text{Relative Growth Rate} = \frac{\text{DBH at time 2} - \text{DBH at time 1}}{\text{time 2} - \text{time 1}}$$

The growing season in New England is limited to the spring through the fall because the low winter air temperatures and frozen soil inhibit tree growth, and deciduous trees drop their leaves in the fall. Thus, using calendar date for time is not necessarily a good indication of the actual amount of time a tree has available to grow, particularly for young trees planted in the fall. To standardize tree growth by the amount of potential growing time the tree has had, we calculated the number of Growing Degree Days (GDD) between the first and last DBH measurement. Growing Degree Days are a standard metric used by farmers, gardeners, horticulturists, and scientists to count the accumulated number of degree-days that organisms have to grow. Growing Degree Days are calculated based on the number of degrees above a certain baseline temperature that occur during a given time period. For each day in the given period, Growing Degrees are calculated as the average of the maximum and minimum temperature for that day, minus the baseline temperature. The values are then summed for each calendar day across the time period of interest. Here we use the baseline temperature value of 41°Fahrenheit (5°Celsius). We acquired daily weather data from the Boston Logan Airport[16] from 2005 to 2015. During this time period, the average number of GDD per year was 2893.3 GDD, with a standard error of 42.7 GDD (range = 2666.7 in 2009 – 3118.6 in 2010).

We limit the dataset to trees for which we have two measurement times, and for which each measurement is precise to one tenth of an inch. The entire dataset for estimating growth consists of 1,845 trees. For all 1,845 trees, the average relative growth rate is 0.26 inches per year (with a

[16] Weather data acquired from Weather Underground, www.wunderground.com.

standard error of 0.007 inches per year). The average relative GDD growth rate is 0.10 inches per GDD (x 1000), with a standard deviation of 0.003 inches per GDD (x 1000).

Young trees have faster relative growth rates (two-sample, two-tailed *t*-test; df = 1355, $t = –3.71$, $p = 0.0002$), and faster relative GDD growth rates (two-sample, two-tailed *t*-test; df = 1542, $t = –4.83$, $p < 0.0001$), than old trees (***Table 4***).

After being transplanted a tree may expend more energy towards developing their root system than growing their stem and branches. We tested whether young trees grew significantly less in the first year after planting compared to later in their development. Young trees tended to have faster growth rates after their first year of growth (***Table 4***), but the difference was only marginally significant for relative growth rate (two-sample, one-tailed *t*-test; df = 55.4, $t = –1.58$, $p = 0.06$), and not significant for relative GDD growth rate (two-sample, one-tailed *t*-test; df = 54.6, $t = –0.55$, $p = 0.29$).

Table 4. Growth rate estimates for young and old trees.
Within a column, values followed by different letter are significantly different, demonstrating that young trees grow significantly faster than old trees.

Dataset	Number of Trees	Relative Growth Rate (inches / year)	Relative GDD Growth Rate (inches / GDD)*1000
Old Trees	481	0.22 ± 0.01 a	0.08 ± 0.004 a
Young Trees	1,364	0.27 ± 0.01 b	0.11 ± 0.004 b
Less than one year	*52*	*0.20 ± 0.05*	*0.10 ± 0.02*
More than one year	*1,312*	*0.28 ± 0.01*	*0.11 ± 0.004*

Young trees planted in the spring season have faster growth rates than trees planted in the summer or fall, both in terms of relative growth rate (ANOVA; df = 2, 1357, F = 11.20, $p < 0.0001$) and relative GDD growth rate (ANOVA; df = 2, 1357, F = 7.35, $p = 0.0007$; ***Table 5***).

Table 5. Growth rate estimates by planting season, for young trees.
Within a column, values followed by different letter are significantly different, demonstrating that young trees planted in the spring grow significantly faster than young trees planted in the summer or fall.

Planting Season	Number of Trees	Relative Growth Rate (inches / year)	Relative GDD Growth Rate (inches / GDD)*1000
Spring	667	0.34 ± 0.02 a	0.13 ± 0.007 a
Summer	443	0.26 ± 0.02 b	0.10 ± 0.009 b
Fall	250	0.24 ± 0.01 b	0.10 ± 0.005 b

Impact of Biological, Environmental, and Socioeconomic/ Community Factors on Growth

We used multiple linear regression to test the influence of the various biological, environmental, and socioeconomic variables on tree growth. Separately for young and old trees, we created full models that incorporated all of the covariates (variables), and then used stepwise model selection based on Akaike Information Criterion (AIC) to find the best-fit model. The step-wise model selection process removes variables from the model that add little to no explanatory power (*i.e.,* variables that do not influence growth rates).

For both young and old trees, species was the covariate that most impacted tree growth rate (***Table 6***). For details about species-specific differences in growth, see ***Species-specific trends in survival and growth*** section, below.

Young trees that were larger when they were planted (*i.e.*, higher initial DBH) had higher growth rates, whereas old trees that were smaller at the time of first measurement (*i.e.*, lower initial DBH) had higher growth rates (***Table 6***). This suggests that the stems of smaller young trees grow more slowly than the stems of larger young trees, probably because they have limited photosynthetic capacity due to their limited leaf area, and because more of their resources are put toward developing roots during the establishment phase. On the other hand, larger old trees spend more of their energy maintaining their tissues than smaller old trees, and thus larger old trees expend proportionally lower amounts of energy increasing the girth of their stems.

Both young and old trees in Residential zones had faster growth rates than trees in other zones (***Table 6***). This complements the survival results, which demonstrate that survival rates for both age classes are higher in residential zones compared to other zones. This provides further support for the influence of increased tree care capacity on the trees' well being.

Additionally, older trees grew faster in areas with newer housing (*i.e.*, Median Year Housing Built), but grew more slowly in areas with increased vacancy rates (***Table 6***). This suggests that trees in areas with newer infrastructure grow faster. Also, we predict that public vandalism, including damage to trees, is higher in areas with increased vacancy rates. Vandalism to tree bark or roots can be very detrimental to trees, and can reduce growth rates.

Table 6. Growth responses to biological, environmental, and socioeconomic variables. Multiple linear regression results of growth rates standardized by Growing Degree Day (GDD growth rate x 1000). Values are relative importance metrics for terms included in the best-fit models. All of the covariates listed were used in the full model; covariates that do not contain a number were not included in the final, best-fit model. Significant covariates have been bolded and shaded **green** if the coefficient estimate is positive (*i.e.*, if the covariate has a positive influence on tree growth), and **red** if the coefficient estimate is negative (*i.e.*, if the covariate has a negative influence on tree growth).

Covariate	Young trees	Old trees
Species	**0.054*** **	**0.103*** **
Initial Tree DBH (inches)	**0.041*** **	**0.008* **
Solar Insolation (MJ / m^2)	0.002#	0.003
Impervious Surface (%)		
Public Tree Wells (count)	0.003#	0.003#
Population Density (# people per ha)	0.005#	
Housing Density (# houses per ha)		
Owner Occupancy Rate (proportion)		
Vacancy Rate (proportion)		**0.014* **
Median Income ($)		
Population Unemployed (proportion)		
Median Year Housing Built (year)	0.001#	**0.013*** **
Zoning, Residential	**0.010*** **	**0.027*** **
Zoning, Commercial		
Zoning, Industrial	0.001	
Zoning, Open Space		
Model Adjusted R^2	0.105	0.150
Sample size (n)	1,350	481

***p<0.001, **p<0.01, *p<0.05, #p<0.1

Species-specific trends in survival and growth

Among the 20,772 publicly owned trees in the City of Cambridge there are at least 140 unique species (for details, see ***Current State of the Urban Forest*** section of the Urban Forest Management Plan). Our survival dataset, with 3,498 individuals, contains 65 unique species, and our growth dataset, with 1,845 individuals, contains 56 species. Not all of the species in our datasets had high enough sample sizes to perform species-level growth and survival analyses. We were able to compare survival rates for species with 50 or more individuals in the survival dataset, and growth rates for species with 40 or more individuals in the growth dataset.

Here we assessed which species survive and grow best across the entire city. As we did for all trees, we assessed species survival rates and growth rates separately by age class (*i.e.*, young and old trees). However, because our dataset is not continuous and does not span the entire range of ages for each species, the survival results from the older trees cannot be directly compared with the results from the younger trees. Our dataset is also limited by the fact that we do not know the actual ages of the older trees, and thus annual survival rates are combined across all sizes of old trees. This may influence our old-tree survival estimates.

Survival Rate Comparison Among Species

IN A NUTSHELL…

- Among young trees, the species that survive best are Callery Pear, Hedge Maple, American Elm, Pin Oak, Littleleaf Linden, and Honeylocust.
- Among the old trees, Honeylocust, Pin Oak, and London Planetree have the highest survival rates.

For young trees, species-specific annual survival rate estimates range from 92.3% per year (Apple) to 100% per year (Callery Pear; ***Table 7***). Among young trees, the species that survive best are Callery Pear, Hedge Maple, American Elm, Pin Oak, Littleleaf Linden, and Honeylocust. Based on these annual survival estimates, the mean life expectancy for these six species ranges from 66 years to over 100 years. However, these numbers may not accurately reflect actual mean life expectancy rates in the City because the analysis is based only on data encompassing the first seven years since these trees have been planted. This type of analysis assumes constant mortality over time, which is not necessarily the case in a city environment. The mean life expectancy values would be accurate if the survival rates were to remain constant over the lifespan of the trees, but we cannot test this claim directly with the dataset available. Although the values may not be accurate for an entire lifetime, they are useful for among-species comparisons.

For the old trees, species-specific annual survival rate estimates from the time these trees were first measured range from 73.0% per year (Norway Maple) to 99.9% per year (Honeylocust; ***Table 8***). Pin Oak and London Planetree also have high survival rates, whereas the survival rate of Littleleaf Linden is rather low. Norway maple has much lower survival then the other species in our study, suggesting that many of them are approaching the end of their natural lifespan.

Table 7. Species-specific annual survival estimates for young trees.
Species are listed in order from the highest to lowest estimated mean annual survival.

Species	Number of trees	Range initial DBH (inches)	Estimated annual survival (mean ± standard error)	Mean Life Expectancy (# years)	Population Half-Life (# years)
Young Overall	***1927***	***2.5–10.4***	***96.7 ± 1.2***	***29.5***	***20.4***
Pear, Callery	50	2.0–4.0	100% ± 0%	>100	>100
Maple, Hedge	59	1.0–2.0	99.5% ± 0.3%	>100	>100
Elm, American	78	1.0–4.0	99.1% ± 0.6%	>100	76.7
Oak, Pin	100	1.5–4.0	98.7% ± 0.7%	76.4	53.0
Linden, Littleleaf	87	1.0–4.1	98.6% ± 0.7%	70.9	49.2
Honeylocust	225	1.0–4.0	98.5% ± 0.7%	66.2	45.9
Elm sp.	110	1.6–3.0	97.6% ± 0.9%	41.2	28.5
Oak, Swamp White	68	1.3–4.0	97.6% ± 1.4%	41.2	28.5
Maple, Red	181	1.0–4.0	96.1% ± 1.2%	25.1	17.4
Lilac, Japanese Tree	68	1.7–3.0	96.0% ± 2.2%	24.5	17.0
Zelkova, Japanese	71	1.8–4.0	95.1% ± 2.1%	19.9	13.8
Cherry, Sargent	66	1.4–3.0	94.8% ± 3.5%	18.7	13.0
Serviceberry	61	1.0–2.0	94.4% ± 3.1%	17.4	12.0
Cherry, Japanese Flowering	73	2.0–4.0	94.2% ± 2.9%	16.7	11.6
Ginkgo	62	1.7–4.0	92.9% ± 3.8%	13.6	9.4
Planetree, London	84	1.0–4.0	92.8% ± 3.1%	13.4	9.3
Apple	53	1.0–2.0	92.3% ± 5.8%	12.5	8.7
All other species combined	417	1.0–4.0	94.1% ± 2.3%	16.4	11.4

Table 8. Species-specific annual survival estimates for old trees.
Species are listed in order from the highest to lowest estimated mean annual survival.

Species	Number of trees	Range initial DBH (inches)	Estimated annual survival (mean ± standard error)	Mean Life Expectancy (# years)	Population Half-Life (# years)
Old Overall	***1571***	***4.2–45.0***	***90.8% ± 5.2%***	***10.4***	***7.2***
Honeylocust	81	5.0–23.0	99.9% ± 0.1%	>100	>100
Oak, Pin	131	5.0–45.0	99.9% ± 0.1%	>100	>100
Planetree, London	46	5.0–43.0	99.7% ± 0.3%	>100	>100
Maple, Red	145	5.0–34.0	96.3% ± 1.8%	26.5	18.4
Pear, Callery	178	5.0–21.0	96.0% ± 2.7%	24.5	17.0
Linden, Littleleaf	174	5.0–39.0	90.3% ± 6.9%	9.8	6.8
Maple, Norway	497	5.0–34.0	73.0% ± 24.4%	3.2	2.2
All other species combined	294	4.2–37.0	93.3% ± 3.9%	14.4	10.0

Growth Rate Comparison Among Species

Among young trees, the fastest growing species are Elm sp. (hybrid) and Pin Oak (***Table 9***), although the growth rates of young Swamp White Oak, Japanese Zelkova, American Elm, Callery Pear, and London Planetree are statistically equivalent. Apple has the lowest growth rate, followed by Serviceberry, Japanese Tree Lilac, Hedge Maple, Littleleaf Linden, and Japanese Flowering Cherry, all of which are statistically equivalent.

Among old trees, the fastest growing species among is Honeylocust, which grows significantly faster than Red Maple or Norway Maple (***Table 10***).

IN A NUTSHELL…

- Among the young trees Elm sp. and Pin Oak grow the fastest.
- Of the six best surviving species of young trees, three of them (Pin Oak, American Elm, and Callery Pear) are amongst the fastest growing species.
- Among the old trees, Honeylocust has the highest growth rate, as well as the highest estimated survival rate. Callery Pear and Littleleaf Linden also have high growth rates, but moderate and poor survival rates, respectively.
- Callery Pear trees planted in the spring grew faster than trees planted in the fall, but the opposite was true for apple trees.

Across all species of young trees, growth rates are higher for trees that were planted in the spring than for trees planted in the summer or fall (***Table 11***). However, when looking at species-specific growth rates, only two species had significantly different growth rates by planting season (***Table 11***):

- Apple (*Malus sp.*) trees that were planted in the fall grew significantly faster than trees planted in the spring.
- Callery Pear (*Pyrus calleryana*) trees that were planted in the spring grew significantly faster than trees planted in the fall.

A few other species demonstrated differences in growth rates by planting season, but the trends were not statistically significant. American Elm, Honeylocust, and Hedge Maple trees planted in the spring tended to have faster growth rates, but more data is needed to confirm this trend.

Table 9. Species-specific growth estimates for young trees.
Relative growth rate and relative GDD growth rate values are mean ± standard error (SE). Within a column, values with different letters have significantly different growth rates. Species are sorted from fastest growth rate to slowest growth rate.

Species	Number of trees	Relative Growth Rate (inches per year)	Relative GDD Growth Rate (inches per GDD)*1000
Young Overall	***1364***	***0.27 ± 0.01***	***0.11 ± 0.004***
Elm sp.	79	0.45 ± 0.04 a	0.18 ± 0.02 a
Oak, Pin	80	0.44 ± 0.03 a	0.18 ± 0.01 a
Oak, Swamp White	51	0.41 ± 0.04 ab	0.16 ± 0.01 ab
Zelkova, Japanese	56	0.36 ± 0.03 abc	0.13 ± 0.01 abc
Elm, American	57	0.36 ± 0.05 abc	0.13 ± 0.02 abc
Pear, Callery	45	0.35 ± 0.04 abcd	0.13 ± 0.01 abc
Planetree, London	55	0.28 ± 0.03 abcd	0.11 ± 0.01 abc
Honeylocust	161	0.27 ± 0.02 bcd	0.12 ± 0.01 abc
Maple, Red	120	0.23 ± 0.02 bcd	0.09 ± 0.01 bc
Cherry, Japanese Flowering	57	0.23 ± 0.04 bcde	0.09 ± 0.02 bcd
Linden, Littleleaf	63	0.21 ± 0.04 bcde	0.09 ± 0.02 bc
Maple, Hedge	50	0.16 ± 0.03 cde	0.05 ± 0.02 cd
Lilac, Japanese Tree	40	0.12 ± 0.04 de	0.04 ± 0.01 cd
Serviceberry	40	0.11 ± 0.04 de	0.04 ± 0.02 cd
Apple	44	0.01 ± 0.06 e	0.00 ± 0.03 d
All other species combined	366	0.26 ± 0.02 bcd	0.10 ± 0.01 bc

Table 10. Species-specific growth estimates for old trees.
Relative growth rate and relative GDD growth rate values are mean ± standard error (SE). Within a column, values with different letters have significantly different growth rates. Species are sorted from fastest growth rate to slowest growth rate.

Species	Number of trees	Relative Growth Rate (inches per year)	Relative GDD Growth Rate (inches per GDD)*1000
Old Overall	**481**	**0.22 ± 0.01**	**0.08 ± 0.004**
Honeylocust	54	0.26 ± 0.02 ab	0.10 ± 0.01 ab
Linden, Littleleaf	58	0.19 ± 0.02 bc	0.07 ± 0.01 bc
Pear, Callery	40	0.17 ± 0.03 bc	0.07 ± 0.01 bc
Maple, Norway	71	0.14 ± 0.02 c	0.05 ± 0.01 c
Maple, Red	56	0.14 ± 0.02 c	0.05 ± 0.01 c
All other species combined	*202*	*0.30 ± 0.01 a*	*0.11 ± 0.01 a*

Table 11. Species-specific relative growth rate by planting season, for young trees.
Values are mean ± standard error GDD growth rate ((inches per GDD)*1000), with sample size in parentheses. Planting season is spring for trees planted March-May, summer for trees planted June-August, and fall for trees planted September-November. The importance of planting season was assessed for each species using ANOVA analysis, followed by Tukey HSD post-hoc tests. Growth rate varied significantly by planting season for species highlighted in **bold** (*P*-value < 0.05). Within a species, values followed by different letters are significantly different. For ease of interpretation, for the species with significantly different growth rates in different planting seasons, the values in **green** pertain to the planting season for which the species has a significantly higher growth rate than the season(s) in **red**.

Species	Spring	Summer	Fall	*P*-value
All young trees	**0.13 ± 0.01 (443) a**	**0.10 ± 0.01 (250) b**	**0.10 ± 0.01 (667) b**	**0.001**
Apple	**-0.11 ± 0.05 (15) b**	**0.03 ± 0.05 (13) ab**	**0.07 ± 0.02 (16) a**	**0.01**
Cherry, Japanese Flowering	0.08 ± 0.03 (28)	0.11 ± 0.02 (8)	0.08 + / 0.02 (21)	0.80
Elm sp.	0.18 ± 0.03 (36)	0.13 ± 0.06 (5)	0.19 ± 0.02 (38)	0.65
Elm, American	0.20 ± 0.03 (19)	0.12 ± 0.04 (6)	0.10 ± 0.03 (32)	0.07
Honeylocust	0.16 ± 0.01 (45)	0.09 ± 0.03 (27)	0.10 ± 0.02 (89)	0.06
Lilac, Japanese tree	0.03 ± 0.03 (7)	0.06 ± 0.03 (5)	0.04 ± 0.02 (28)	0.87
Linden, Littleleaf	0.14 ± 0.03 (23)	0.07 ± 0.03 (11)	0.06 ± 0.03 (29)	0.12
Maple, Hedge	0.11 ± 0.02 (31)		0.06 ± 0.01 (14)	0.07
Maple, Red	0.10 ± 0.01 (29)	0.07 ± 0.02 (22)	0.10 ± 0.01 (69)	0.46
Oak, Pin	0.20 ± 0.02 (28)	0.19 ± 0.03 (22)	0.15 ± 0.02 (30)	0.23
Oak, Swamp White	0.22 ± 0.05 (20)	0.09 ± 0.06 (9)	0.15 ± 0.02 (22)	0.12
Pear, Callery	**0.17 ± 0.01 (18) a**	**0.18 ± 0.02 (6) ab**	**0.08 ± 0.03 (20) b**	**0.01**
Planetree, London	0.14 ± 0.02 (10)	0.08 ± 0.02 (18)	0.14 ± 0.02 (25)	0.13
Serviceberry		0.06 ± 0.04 (7)	0.04 ± 0.02 (29)	0.62
Zelkova, Japanese	0.16 ± 0.03 (13)	0.11 ± 0.03 (14)	0.14 ± 0.01 (29)	0.19

Future steps/ recommendations

The analyses and results presented in this document provide various metrics with which to assess the overall health of an urban forest. The growth and survival rates we present for street trees in the City of Cambridge can serve as baseline values against which the outcomes of management strategies and programs can be tested.

Overall, the survival rate of street trees in the City of Cambridge is on the higher end of scientific estimates in other cities. Whereas the average lifespan of an urban tree is often claimed to be 7–13 years (*18*), a recent scientific study puts a more realistic estimate at 19 to 28 years (*11*). Here, we calculated the mean life expectancy for young trees in the City to be 29.5 years, and we are 95% confident that the true mean life expectancy for young trees in the City is at least 15.6 years.

Here we provide some management recommendations to increase survival rates and to promote faster growth rates.

1. When to plant: Although the timing of planting did not influence survival rate for the trees in our study, it did affect growth rates. In general, trees planted in the spring grow significantly faster than trees planted in the summer or fall. However, Apple trees grow faster when planted in the fall.
2. What to plant: Plant larger diameter trees for faster growth rates. For young trees, the species with the highest survival rates are Callery Pear, Hedge Maple, and American Elm. The species with the lowest survival rates as young trees are Apple, London Planetree, and Ginkgo. For the young trees, the species that grow the fastest are Elm sp. (hybrid Elms), Pin Oak, and Swamp White Oak. The species with the lowest growth rates are Apple, Serviceberry, and Japanese Tree Lilac.
3. Where to plant: Tree growth and survival rates are higher in certain areas of the City.
    - Both survival and growth rates are higher in Residential areas compared to Industrial areas and Other (primarily office) areas. Survival is also high in Commercial zones. These results suggest that tree care by abutters improves tree growth and survival, whereas stem and root damage reduces survival.
    - Young tree survival rates are higher in areas with lower light conditions. In areas with high light, the placement of temporary shading structures may improve survival rates. Alternatively, a more intensive watering regime may improve survival rates of trees growing in high light conditions.
    - Young tree survival rates are also lower in areas with higher median income and higher public tree well counts. These results warrant further exploration, but may be due, at least in part, to higher levels of construction in these areas. It may also suggest that proportional commitment to tree care is lower in these areas.

Recommendation for data collection efforts

The analysis presented here is for street trees only. We did not include park trees in the study because our park tree dataset was limited, and the accuracy of the results was uncertain. Many of the parks in the City have not been inventoried for almost a decade, and it is much more difficult to track individuals trees in the park from historical maps. We recommend updating the inventory of trees in the parks and open spaces. As it is difficult to keep track of the trees in the parks, we also recommend using tree tags to mark the trees, if possible. This would ensure that tree measurements in the future could be matched to the same tree. To assess growth and survival of these park trees, we recommend that they be revisited and re-measured approximately 3 to 5 years after the initial inventory.

We also encourage the use of trained volunteers for large data collect efforts. We demonstrate that volunteers collect accurate data when they are provided with the right equipment and the right training. Having a large volunteer base can enable a large amount of data to be collected in a short amount of time.

Recommendation for outreach/ education
Trees in the "other" zones of the city (including offices and educational areas) and the industrial zones had lower survival and growth rates than in residential and commercial areas. We suspect that the abutters in these areas are not caring for the trees, perhaps because they do not know that the can, and should. We recommend focusing an educational outreach effort in the industrial, educational, and office areas of the city.

Recommendation for planting
Currently, there are 21,890 tree wells in the City, and of those 1,258 do not contain a live tree (refer to the Urban Forest Management Plan ***Current State of the Urban Forest*** document). That means 20,632 wells contain a live tree. Our calculated mean annual survival rate of 96.7% means that the mean annual mortality rate is 3.3%. Thus, of the 20,632 wells that contain a live tree, on average 681 of those trees die every year. This calculation is only a rough estimate because it assumes that the annual mortality rate is constant across a tree's lifetime and does not vary across the city. Although it is only a rough estimate, these calculations suggest that although the City plants ~300 trees per year, there is still a net increase of ~381 wells that do not contain a live tree. Thus, if possible, we recommend planting more than 300 trees per year.

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Appendices

Appendix A. Land use categories and simplified zoning categories in the City of Cambridge.

Land Use Code, Land Use Description, and Land Use Category were obtained from the City of Cambridge (https://www.cambridgema.gov/CDD/zoninganddevelopment/Zoning/Maps). For the analyses presented in the current document, we simplified the Land Use Category into five different Zoning Categories, including *Residential*, *Commercial*, *Industrial*, *Open Space*, and *Other*.

Land Use Code	Land Use Description	Land Use Category	Zoning Category
13	MULTIUSE-RES	Mixed Use Residential	Residential
31	MULTIUSE-COM	Mixed Use Commercial	Commercial
41	MULTIUSE-IND	Mixed Use Industrial	Industrial
101	MXD SNGL-FAM-RE	Mixed Use Residential	Residential
101	SNGL-FAM-RES	Residential	Residential
104	MXD TWO-FAM-RES	Mixed Use Residential	Residential
104	TWO-FAM-RES	Residential	Residential
105	MXD THREE-FM-RE	Mixed Use Residential	Residential
105	THREE-FM-RES	Residential	Residential
106	RES-LAND-IMP	Transportation	Other
111	MXD 4-8-UNIT-AP	Mixed Use Residential	Residential
111	4-8-UNIT-APT	Residential	Residential
112	MXD >8-UNIT-APT	Mixed Use Residential	Residential
112	>8-UNIT-APT	Residential	Residential
113	ASSISTED-LIV	Assisted Living/Boarding House	Residential
121	BOARDING-HSE	Assisted Living/Boarding House	Residential
121	MXD BOARDING-HS	Mixed Use Residential	Residential
130	RES-DEV-LAND	Vacant Residential	Residential
131	RES-PDV-LAND	Vacant Residential	Residential
132	RES-UDV-LAND	Vacant Residential	Residential
140	CHILD-CARE	Commercial	Commercial
300	HOTEL	Commercial	Commercial
302	INN-RESORT	Commercial	Commercial
304	NURSING-HOME	Health	Residential
316	WAREHOUSE	Commercial	Commercial
323	SH-CNTR/MALL	Commercial	Commercial
324	SUPERMARKET	Commercial	Commercial
325	RETAIL-STORE	Commercial	Commercial
326	EATING-ESTBL	Commercial	Commercial
327	RETAIL-CONDO	Commercial	Commercial
330	AUTO-SALES	Commercial	Commercial
331	AUTO-SUPPLY	Commercial	Commercial
332	AUTO-REPAIR	Commercial	Commercial
334	GAS-STATION	Commercial	Commercial

Appendix A cont.

Land Use Code	Land Use Description	Land Use Category	Zoning Category
335	CAR-WASH	Commercial	Commercial
336	PARKING-GAR	Transportation	Other
337	PARKING-LOT	Transportation	Other
340	GEN-OFFICE	Office	Other
341	BANK	Commercial	Commercial
342	MEDICAL-OFFC	Health	Other
343	OFFICE-CONDO	Office	Other
345	RETAIL-OFFIC	Office	Other
346	INV-OFFICE	Office	Other
353	FRAT-ORGANIZ	Commercial	Commercial
362	THEATRE	Commercial	Commercial
370	BOWLING-ALLY	Commercial	Commercial
375	TENNIS-CLUB	Commercial	Commercial
390	COM-DEV-LAND	Vacant Commercial	Commercial
391	COM-PDV-LAND	Vacant Commercial	Commercial
392	COM-UDV-LAND	Vacant Commercial	Commercial
400	MANUFACTURNG	Industrial	Industrial
401	WAREHOUSE	Industrial	Industrial
404	RES-&-DEV-FC	Office/R&D	Other
406	HIGH-TECH	Office/R&D	Other
407	CLEAN-MANUF	Industrial	Industrial
409	INDUST-CONDO	Industrial	Industrial
413	RESRCH IND CND	Industrial	Industrial
422	ELEC GEN PLANT	Utility	Industrial
424	PUB UTIL REG	Utility	Industrial
428	GAS-CONTROL	Utility	Industrial
430	TELE-EXCH-STA	Utility	Industrial
440	IND-DEV-LAND	Vacant Industrial	Industrial
442	IND-UDV-LAND	Vacant Industrial	Industrial
920	Parklands	Public Open Space	Open Space
930	Government Operations	Government Operations	Other
934	Public Schools	Education	Other
940	Private Pre & Elem School	Education	Other
941	Private Secondary School	Education	Other
942	Private College	Higher Education	Other
942	Higher Ed and Comm Mixed	Mixed Use Education	Other
943	Other Educ & Research Org	Higher Education	Other
953	Cemeteries	Cemetery	Open Space
955	Hospitals & Medical Offic	Health	Other

Appendix A cont.

Land Use Code	Land Use Description	Land Use Category	Zoning Category
956	Museums	Higher Education	Other
957	Charitable Services	Charitable/Religious	Other
960	Religious	Charitable/Religious	Other
971	Water Utility	Utility	Industrial
972	Road Right of Way	Transportation	Other
975	MBTA/Railroad	Transportation	Other
995	Private Open Space	Privately-Owned Open Space	Open Space
1014	SINGLE FAM W/AU	Residential	Residential
1067	RES-COV-PKG	Transportation	Other
1322	RES-UDV-PARK (OS) LN	Vacant Residential	Residential
3922	CRMCL REC LND	Vacant Commercial	Commercial
9421	Private College Res Units	Education Residential	Residential
9751	MBTA/Railroad	Transportation	Other