# Urban Tree Mortality: A Literature Review

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**Abstract.** Tree survival is a performance metric for urban forestry initiatives, and an understanding of the factors that influence mortality can help managers target resources and enhance survival. Furthermore, urban tree planting investments depend on tree survival to maximize ecosystem services. In this literature review, we categorized factors commonly associated with urban tree mortality and summarized mortality rates published in 56 studies, focusing on studies of trees along streets, in yards, and in landscaped parks. Study designs included quantitative field monitoring of uneven-aged tree populations and tracking planting cohorts of even-aged trees, as well as qualitative analyses. Annual mortality rates ranged from 0.6 to 68.5% for cohort studies and 0 to 30% for repeated inventories of uneven-aged trees. The 1st, 2nd, and 3rd quartiles of annual mortality were 2.8 to 3.8%, 4.4 to 6.5%, and 7.1 to 9.3% for planting cohorts, and 1.6%, 2.3 to 2.6%, and 3.0 to 3.3% for repeated inventories of uneven-aged trees (ranges reflect studies that reported a range for the time period or mortality rate). For cohort studies, annual mortality tended to be highest during the first five years after planting. The most commonly cited biophysical factors associated with mortality were taxa (15 articles), tree size/age (13 articles), and site characteristics (12 articles). The most commonly cited human-related factors were stewardship, maintenance, and vandalism (15 articles). More long-term studies are needed to investigate how site characteristics influence mortality, including rarely examined soil and microclimate characteristics. Future research should also examine institutional structures related to mortality outcomes, as well as parcel-level sociodemographic factors and resident behaviors.

**Key Words.** Ecological Monitoring; Street Tree; Tree Death; Tree Demography; Tree Population; Tree Survival; Urban Park; Yard Tree.

## INTRODUCTION

In urban forestry, substantial resources are invested in the planting and maintenance of trees. For instance, 81% of municipalities in the United States allocate public dollars to tree planting and care, which amounts to an estimated $37.50 annually per public tree (street trees, park trees, and trees in other public places; Hauer and Peterson 2016). In total, 45% of municipal tree budgets are spent on planting and care-related activities, and another 23% is spent on removal (Hauer and Peterson 2016). These efforts aim to enhance the functional lifespan of trees, maximizing the many environmental, economic, and societal benefits provided by urban woody vegetation (Pataki et al. 2011; Roy et al. 2012). The success of these planting and maintenance efforts can be measured by tree survival (Roman et al. 2013; Roman et al. 2016), as survival is essential to achieve the intended ecosystem services associated with tree maturity (Ko et al. 2015b; Widney et al. 2016). Continuing research on factors that increase or decrease survival provides insights into the basic demographic processes of urban forest population dynamics. Indeed, the population dynamics and growing conditions of planted trees in landscaped and heavily built-up urban areas are quite dissimilar from trees in natural forests (i.e., trees in rural, wildland settings) (Urban 2008; Roman et al. 2016). Translating urban tree mortality research into practice can ultimately strengthen management of individual trees and planting projects as well as the urban forest system as a whole.

Research on tree mortality from natural forests suggests that trees often die as a result of many different additive and interacting factors. As trees age, the impact of chronic and acute stressors accumulates, which ultimately leads to tree death (Franklin et al. 1987). This interpretation of the mortality process, supported by patterns in long-term growth (Das et al. 2007), was described by Manion (1981) as the "disease decline spiral" and later modified by Franklin et al. (1987) as the "mortality spiral." In Manion's (1981) classic book, "urban environment" was listed as a predisposing factor, yet the "urban environment" encompasses a wide range of biophysical and

socioeconomic conditions and causal mechanisms. Furthermore, in the urban context, the word "mortality" connotes both death and pre-death removal of trees (Roman et al. 2016); whereas removal is not part of natural (and unlogged) forest systems. In other words, purposeful removals by humans can be a key element of urban tree mortality. Indeed, for many urban tree mortality field monitoring studies, mortality has been defined as a combination of trees observed standing dead plus those observed removed (e.g., Nowak et al. 2004; Lima et al. 2013; Roman et al. 2014a; Ko et al. 2015a; Escobedo et al. 2016; Boukili et al. 2017). Moreover, the site conditions found in urban areas can often be more challenging than those found in natural forest areas, such as compacted soils and low nutrient availability (Urban 2008; Scharenbroch et al. 2017). At the same time, urban trees in maintained and landscaped areas (i.e., not urban trees in closed-canopy wooded park settings or afforested areas) can be given advantages, such as reduced competition for light, as well as supplemental irrigation and fertilizer. Indeed, such tree maintenance is fundamental to arboricultural best practices (Ferrini et al. 2017). Considering the many stresses and advantages for trees growing in the "urban environment" of Manion's (1981) book, a comprehensive literature review of the factors affecting urban tree mortality is warranted to re-conceptualize the mortality process in the urban context.

Given the complicated nature of the social-ecological systems in which urban trees exist (Pickett et al. 1997; Mincey et al. 2013; Vogt et al. 2015a), factors influencing mortality can be described as being human-related, biophysical, or a combination of the two. Biophysical predictive factors of urban tree mortality include species or other taxonomic groups, functional groups (e.g., hardwoods vs. softwoods), drought tolerance, tree size, and time since planting (e.g., Nowak et al. 2004; Koeser et al. 2014; Roman et al. 2014a; Roman et al. 2014b). Human-related factors include land use, construction and development, and stewardship or maintenance activities (e.g., Hauer 1994; Nowak et al. 2004; Boyce 2010; Lawrence et al. 2012; Koeser et al. 2014; Roman et al. 2014b). Human-related and biophysical factors can be deeply coupled. For instance, species and site selection choices by tree professionals and residents relate to later susceptibility to drought, but irrigation may enable trees to survive in regions with varying precipitation patterns (Roman

et al. 2014b; Koeser et al. 2014; Mincey and Vogt 2014; Vogt et al. 2015a; Martin et al. 2016).

Urban tree mortality can also be classified by life stages, such as establishment-related losses (Richards 1979). The establishment period—the first few years after tree planting (Sherman et al. 2016; Levinnson et al. 2017; Harris and Day 2017; Leers et al. 2018) —is generally viewed as the life stage with the highest mortality for urban trees and has thus been the focus of many mortality studies (e.g., Nowak et al. 1990; Struve et al. 1995; Koeser et al. 2014; Roman et al. 2014b; Roman et al. 2015; Widney et al. 2016). The establishment stage for planted urban trees parallels with classic concepts in forest ecology, where younger and smaller trees have the highest mortality (Franklin et al. 1987; Lines et al. 2010). Trees in natural forests generally have a U-shaped or Type III mortality curve (e.g., Coomes and Allen 2007; Lorimer et al. 2001; Metcalf et al. 2009; Lines et al. 2010). The U-shaped mortality curve has high mortality rates for small trees, low for mid-sized and mature trees, and rising mortality rates for very large trees, whereas the Type III curve similarly has high mortality rates for small trees, and low mortality rates for all other sizes (Harcombe 1987). For either mortality curve shape, forest ecology studies generally report annual mortality rates of 1 to 3%, or even less, for mature overstory or canopy trees (e.g., Harcombe and Marks 1983; Condit et al. 1995; Lorimer et al. 2001). Following in this reasoning, Lugo and Scatena (1996) grouped causal factors for mortality in natural forests in the tropics based on intensity levels, with background annual tree mortality less than 5% and catastrophic greater than 5%. In the urban context, catastrophic factors include disease outbreaks (Poland and McCullough 2006), major storms (Staudhammer et al. 2011), and even war (Laçan and McBride 2009; Stilgenbauer and McBride 2010). Background causes are more gradual and could include a tree's slow decline due to construction-related stress or other adverse site conditions (Koeser et al. 2013). Yet it is possible that the background rate of mortality is higher in urban environments compared to natural forests. For instance, a previous meta-analysis of street tree survival found typical annual mortality to be 3.5 to 5.1% (Roman and Scatena 2011), while Nowak et al. (2004) observed 6.6% annual mortality across all land uses in Baltimore, MD (including both planted trees in landscaped areas and naturally regenerating trees in natural

areas). Evaluating what rates of mortality are fairly typical for urban trees, and what rates are catastrophic, can help managers interpret program performance and researchers design realistic projection models (Roman 2014; Roman et al. 2016).

Tree mortality is also a fundamental component of managing urban forest population cycles: planting, growth, pruning, removal, and replacement. In heavily managed portions of the urban forest, such as streetscapes, yards, and landscaped parks, human interventions drive tree population cycles (Roman et al. 2016; Roman et al. 2018). Several models have incorporated mortality rates into projections to assist urban forest managers with decision-making about planting and removal actions. For instance, Miller and Marano (1984) and Bartsch et al. (1985) used tree inventory data combined with user-defined planting, growth, mortality, and removal rates to present street tree population simulations. These models were designed to help meet management objectives related to costs and desired benefits, but they are part of software programs no longer available to managers. More recently, researchers have proposed several projection models to assist with planning for tree removals, replacements, and pesticide treatment regimens due to *Agrilus planipennis* (emerald ash borer, EAB), which threatens widely planted *Fraxinus* spp. (Hauer 2012; VanNatta et al. 2012; Sadof et al. 2017). Another projection example is the i-Tree Forecast model (currently part of i-Tree Eco), which uses urban forest inventory data, default or user adjusted mortality rates, and species/location specific growth models to estimate forest structure and ecosystem services produced under alternative planting scenarios (Nowak et al. 2013). Similarly, projected ecosystem services for million tree planting campaigns in New York City, NY and Los Angeles, CA have assumed mortality scenarios (Morani et al. 2011; McPherson et al. 2008). Each of these projections is essentially a demographic population model: a simulation of population size and structure over time due to adding and subtracting individuals (Roman et al. 2016). Yet as Morani et al. (2011) pointed out in their projection model for tree planting in New York City, "the main limit for the population projector" was the lack of empirical mortality rate information. Furthermore, past research has shown that assumed survival rates in ecosystem services models can be higher than actual rates (Roman et al. 2014b; McPherson 2014; Ko et al. 2015a; Ko et al.

2015b). The potential value of urban forest population projection models is their capacity to reasonably predict urban forest changes (and associated benefits) under varying scenarios. Urban forest population models can enable managers to weigh the trade-offs regarding when, where, and how much to plant, and illustrate how maintenance and removal decisions relate to decadal-scale population cycles.

Urban foresters, ecologists, and arborists need accurate mortality information from empirical field data to understand the process of urban tree death, improve best management practices, and enhance projection models. Particularly in the context of maximizing return-on-investments of public dollars, survival rates are an important yet missing piece of cost-benefit considerations for municipalities (McPherson and Simpson 2002; McPherson and Kendall 2014; Ko et al. 2015b; Widney et al. 2016). Knowing the survival rates for public and private trees planted by municipalities, nonprofits, homeowners, and other parties is crucial to not only justifying expenditures on tree planting, but also to estimating the benefits these trees will provide to city residents into the future (Widney et al. 2016). In this review, we gathered existing literature on urban tree mortality to: (1) summarize reported mortality and survival rates to determine what levels of mortality could be considered typical in urban forests; and (2) identify and categorize biophysical and human factors associated with urban tree mortality.

## METHODS

### Literature Search
We conducted a literature search to find studies reporting urban tree mortality field data. We carried out systematic keyword and article title searches of urban forestry, urban ecology, and arboriculture journals using Web of Science, ScienceDirect, JSTOR, Google Scholar, the US Forest Service's TreeSearch, and the Urban Forestry database at the University of Minnesota library. We searched for prospective articles in non-English languages by searching in Google Scholar, where non-English publications are better represented (Jascó 2005), as well as using the "all languages" options in the search engines listed above. In addition to the keyword searches, we conducted an exhaustive search (i.e., we scanned the titles and abstracts of all publications) of all volumes of *Journal of Arboriculture/Arboriculture & Urban Forestry*

(1976 to present; the publication of the International Society of Arboriculture was re-named to the latter in 2006), *Arboricultural Journal* (1965 to present), *Cities and the Environment* (2008 to present), and *Urban Forestry & Urban Greening* (2002 to present), since these are the journals most likely to have studies of interest. The date range for searching was "all time" for keyword searches, or the earliest publications for the comprehensive journal searches. This included material available online through December 2017.

We carried out keyword and title searches using the following terms: tree mortality, tree survival, tree survivability, tree survivorship, tree death, tree removal, tree population projection, tree population model, tree establishment, and tree failure. These terms were joined by the search term "AND" with the words urban, city, street, and yard. After identifying initial articles, more potential articles were found using "backward chaining" (searching the literature cited in the starting manuscript, then moving backward through a chain of references) and "forward chaining" (finding articles which cite the starting manuscript, following the chain of references forward). Both "chaining" techniques can be successful for comprehensive literature searches (Booth 2008). Forward chaining was conducted using Google Scholar, as this search engine searches a broad range of literature and is more likely to locate "gray literature" such as theses, extension articles, and conference proceedings (Haddaway 2015). The inclusion of "gray literature" was evaluated by researchers on a case-by-case basis. Theses which were later published in journals were excluded.

Studies were considered eligible for inclusion in our literature review if they: (1) examined tree mortality in landscaped or heavily built-up urban areas, such as trees in sidewalks, parking lots, yards, and manicured parks; and (2) were observational studies in real-world urban conditions. We excluded arboricultural planting experiments, such as tests of cultivar performance (e.g., Gerhold 2007), studies that focused completely on remnant or afforested forest fragments (e.g., Dislich and Pivello 2002), and studies which stated mortality assumptions in projection models (e.g., McPherson 2008). We included some plot-based studies that examined tree mortality across an entire city, and therefore included wooded park lands, but we focused our discussion on the other land uses.

## Examining Mortality Information

We targeted urban forestry studies that presented data on mortality or survival rates and the influential factors associated with mortality. These factors could have been examined either quantitatively or qualitatively. Field-based monitoring studies generally fell into two study design categories: repeated inventories of uneven-aged tree populations and planting cohort studies of even-aged trees. If a study examined a population of trees of various size and age classes by comparing data from a current inventory with data from a prior inventory (either conducted by the same researchers or pulled from existing records), then we considered it to be a repeated inventory of uneven-aged trees. This category included monitoring i-Tree Eco style plots and repeated street tree inventories. If a study examined the survival and mortality of a group of trees planted around the same time, then we considered it to be a planting cohort study of relatively even-aged trees. In the context of planted urban trees, "age" means time since planting. Furthermore, some planting cohort studies examined groups of trees that were planted over a small range of years, which we considered to be a multi-year cohort. When we analyzed cohort studies, we considered the establishment phase to be the first five years since planting and the post-establishment phase to be over five years since planting. Some urban tree mortality studies did not fall into either category and therefore could not be analyzed for mortality rates *per se*. However, since they still pertained to real-world mortality and provided information on factors like human behavior and natural disasters, we included them in our review, the results, and discussion. These studies included surveys of residents and urban tree managers, one-time inventories following storm events, assessments of removal records, and a dendrochronology study.

For all planting cohort study data we calculated, annual mortality, $q_{annual}$, and cumulative survivorship, $l_t$, were defined as

$$q_{annual} = 1 - l_t^{1/t}$$

where $t$ is the number of years since planting and $l_t$ is the proportion of the original population remaining alive at time $t$ (Roman and Scatena 2011; Roman et al. 2016). That original population is represented by baseline data, either the first inventory (for repeated inventory studies) or planting records (for planting cohort studies). For repeated inventory studies of

uneven-aged trees, annual mortality was calculated using provided periodic survival rate $p_t$ (i.e., the proportion surviving over the time interval $t$) and the equation

$$p_{annual} = p_t^{1/t}$$

(Roman et al. 2016). For both cohort studies and repeated inventory studies of uneven-aged trees,

$$q_{annual} = 1 - p_{annual}$$

(Roman et al. 2016) was used. We assumed a constant rate of mortality when calculating annual mortality rates over a specified time period from a given study (Roman and Scatena 2011). We also summarized how the studies we reviewed defined and calculated mortality.

To summarize the typical mortality rates provided in the literature, we calculated the quartiles, since these summary statistics are less influenced by outliers than the mean. We did not use weighted quartiles by sample size because we did not want to attribute more weight to studies of larger tree populations based solely on that metric. If studies gave a range of mortality rates or study period lengths (i.e., time since last inventory for repeated inventories of uneven-aged trees, or time since planting for multi-year planting cohort studies), the minimum and maximum values were used in calculations, and we reported the corresponding lower and higher quartile values. For such studies that reported ranges, lower values represent the lowest possible interpretation of annual mortality, and higher values represent the highest possible interpretation of annual mortality. We did not use the mid-point because we could not be certain that the mid-point was representative of the underlying range of data. If a study provided mortality rates for one or more sub-groupings, we retained these sub-group values to use in summary tables and quartile calculations if (1) this was the only information reported; or (2) the sub-groupings were based on time since planting or tree size. For planting cohort studies, we used the quartile summary statistics for establishment and post-establishment mortality rates to create survivorship curves for fairly typical annual mortality (50th percentile), worse-than-normal (75th percentile), and better-than-normal (25th percentile). For two planting cohort studies that provided annual mortality information for different age classes (Lu et al. 2010; Roman et al. 2016), we created mortality curves by

graphing annual mortality against time since planting. Likewise, for repeat inventories of uneven-aged trees, when annual mortality information was provided for varying size classes (Nowak 1986; Nowak et al. 2004; Roman et al. 2014a), we created mortality curves by graphing annual mortality rates against size class (using diameter at breast height, dbh).

Factors associated with mortality outcomes from quantitative and qualitative studies were categorized as either human-related or biophysical and into sub-categories within these two major categories, recognizing the potential for interactive and coupled effects and the multi-scalar patterns in which they operate. We then grouped these factors as predisposing, inciting, or contributing, following the disease-decline model from Manion (1981). Predisposing factors represent the human and biophysical context at the time of planting. These conditions can then create vulnerabilities to inciting factors, which are short-term stressors that impact tree vigor. The inciting factors, in turn, create vulnerabilities to contributing factors, which are the direct mechanisms leading to tree mortality.

In addition to short summary tables in which we presented mortality rate quartiles and factors associated with mortality, we created three comprehensive tables: one outlining mortality rates in cohort studies, one outlining mortality rates in repeat inventory studies, and a final table summarizing studies that provided statistical analysis of factors associated with mortality. In order for a study to be included in the quartile calculations for annual mortality rates, it had to report annual mortality rates (or sufficient information to calculate annual rates) and a time interval. Studies that did not provide mortality information, time intervals, or whose methodologies were vastly different than the majority of papers, were excluded from these tables but were still considered in other summary results and discussion of the literature reviewed.

## RESULTS AND DISCUSSION

### Characteristics of the Literature

Fifty-six studies were analyzed. Fifty-two of the studies were published in peer-reviewed journals, three were internal reports or extension articles, and one was a master's thesis. Eighteen studies were published in the *Journal of Arboriculture/Arboriculture*
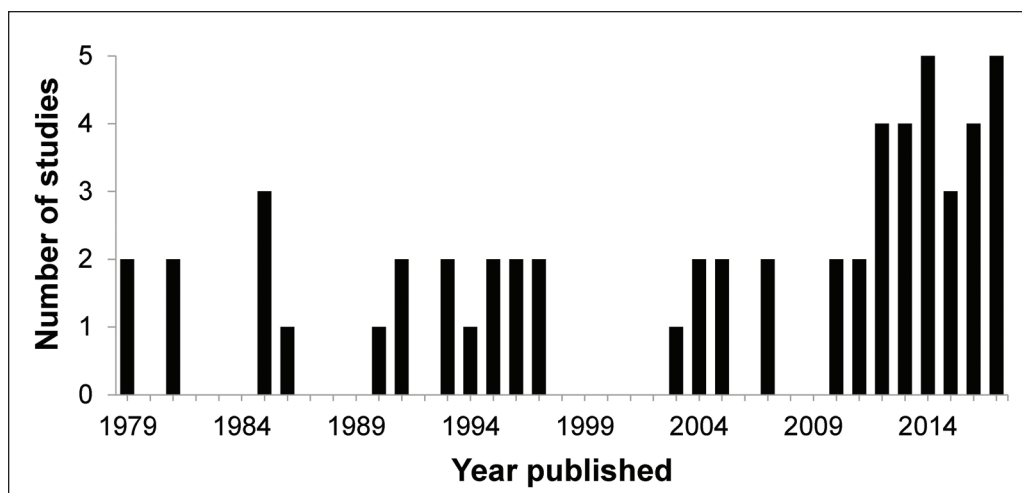
Figure 1. Years in which the urban tree mortality studies reviewed were published (1979 to 2017).

*& Urban Forestry*, and thirteen were published in *Urban Forestry & Urban Greening*. The publication dates spanned thirty-eight years (1979 to 2017) with thirty-one published between 2007 and 2017 (Figure 1). Forty-one of the studies were conducted in the continental United States (Table 1). Almost a third of the studies examined trees in urban areas located in the warm temperate–fully humid–hot summer climate zone (Kottek et al. 2006; Figure 2). There was a lack of studies in equatorial, arid, and very cold climates. Despite searching using the "all language" function, we did not find non-English studies meeting our criteria for review. Twenty-five of the studies focused solely on street trees, four studied trees on private residential properties (e.g., lawns/yards), three studied park trees, twenty studied trees on a mix of these three planting site types, and four did not specify site types. Street trees were the most common, likely because municipal or non-profit street tree planting and inventory records are often more readily available than records for park trees, and public street trees are logistically easier to monitor than trees on private properties, as the latter require permission to access.

Thirty-three articles provided sufficient information for us to calculate annual mortality rates, which we grouped according to study type: repeated inventory of uneven-aged trees or planting cohort of relatively even-aged trees (Table 2). Some articles provided data on both types of tree studies. Eighteen discussed repeated inventories (summarized in detail in Appendix Table 2), and twenty-one discussed planting cohort monitoring studies (Appendix Table 1). Of the planting cohort monitoring studies, sixteen examined trees within five

**Table 1. Countries where urban tree mortality studies were conducted.**

| Country | Number of studies |
|---|---|
| U.S.A. | 41 |
| Canada | 3 |
| China | 3 |
| New Zealand | 2 |
| South Africa | 1 |
| Chile | 1 |
| Belgium | 1 |
| Thailand | 1 |
| Australia | 1 |
| Finland | 1 |
| England | 1 |

years of planting (i.e., establishment phase) and eight examined trees planted over five years prior (i.e., post-establishment phase; Table 2). Forty-one studies provided sufficient information for categorizing the human and biophysical factors significantly associated with mortality. Twenty-six studies also examined growth, which we did not examine in-depth in this review.

## Mortality Definitions

When gathering and reviewing urban mortality and survival data, it is imperative to clearly define mortality and survival. Almost all of the studies in our review define mortality as death or removal of the original tree (e.g., a tree that was listed in a prior inventory or planting record), but this was not always explicitly stated. The only study which did not include removals in the definition of mortality was Jack-Scott
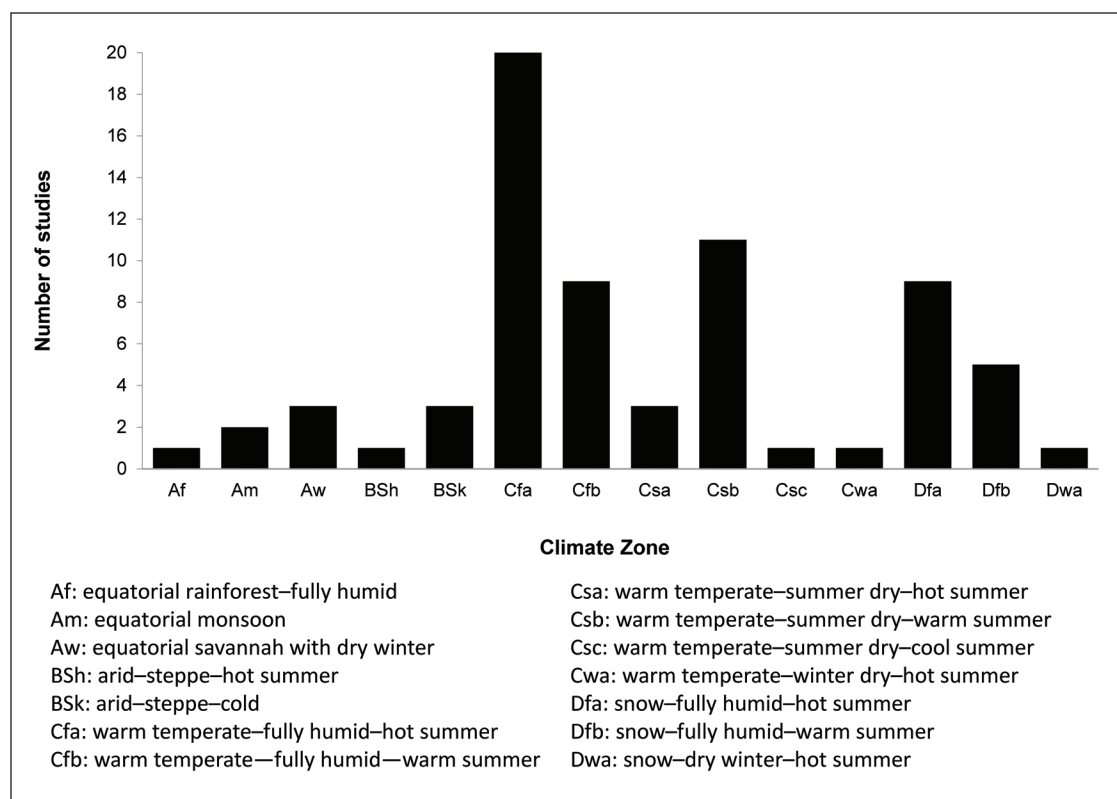
**Figure 2. Climate zones where data was collected for the reviewed studies. Climate zones are based on the Köppen-Geiger climate classification system where the 3-letter abbreviations correspond to main climate, precipitation, and temperature (after Kottek et al. 2006).**

Table 2. Quartiles of annual mortality rates for different study types: repeat inventory of mixed-aged existing trees vs. planting cohort. Planting cohort studies are further broken down into all studies, those reporting establishment mortality (≤ 5 years after planting) and those reporting post-establishment mortality (> 6 years post-planting). When a given study reported a range of years or a range of mortality values, we used the lower annual mortality value in the "lower" row and the higher annual mortality value in the "higher" row.

| Study type | Number of studies | Lower or higher annual mortality results used | Annual mortality (%) range and quartile | | | | |
|---|---|---|---|---|---|---|---|
| | | | Min. | 1st | Median | 3rd | Max. |
| Repeat inventory | 18 | lower | 0.00 | 1.57 | 2.28 | 3.02 | 30.00 |
| | | higher | 0.00 | 1.59 | 2.59 | 3.30 | 30.00 |
| Planting cohort | | | | | | | |
| all | 21 | lower | 0.60 | 2.81 | 4.40 | 7.08 | 68.47 |
| | | higher | 0.60 | 3.76 | 6.48 | 9.33 | 68.47 |
| establishment | 16 | lower | 1.25 | 3.96 | 6.60 | 9.33 | 68.47 |
| | | higher | 2.74 | 5.02 | 7.00 | 10.43 | 68.47 |
| post-establishment | 8 | lower | 0.60 | 1.50 | 2.76 | 3.81 | 4.60 |
| | | higher | 0.60 | 1.53 | 3.76 | 4.73 | 11.22 |

(2012), which analyzed mortality of planted trees in terms of only the trees observed standing dead (i.e., not removals). In another example of defining mortality that differed somewhat from the norm, Koeser et al. (2014) studied trees that were part of a Florida Forest Service planting program that has a policy of inspecting and replacing trees that die within the first year; survival of replacement trees was included with survival of the original trees in that study's analysis. This procedure may be responsible for the high survival rate of the trees. Lu et al. (2010) also included replacement trees in survival calculations for New York City, NY, such that street trees replaced during the initial contractor guarantee were tracked alongside original trees for survival monitoring after two years (N. Sonti, personal communication), although this was not explicitly stated in the article. For yard tree giveaway programs, definitions of mortality can be complicated by the fact that distributed trees are planted by residents and thus might never get planted at all, leading to mortality rate calculations that use the number of trees distributed (not the number planted) as the denominator (Roman et al. 2014b; Ko et al. 2015a; Roman et al. 2016). For instance, with yard tree monitoring for the same shade tree program in Sacramento, CA, Ko et al. (2015a) used trees distributed as the denominator, whereas Roman et al. (2014b) used trees planted, largely due to practicalities of the Ko et al. (2015a) analysis being unable to discern whether trees observed "missing" in the early 1990s were cases of post-planting mortality vs. failure to plant.

## Mortality Rates

We summarized information from studies providing annual mortality rates (or sufficient information for us to calculate rates) and time periods in Appendix Tables 1 and 2. For the eighteen studies of repeated inventories of uneven-aged trees, we found the annual mortality rates ranged from 0% (Nowak 1986; Staudhammer et al. 2011; Roman et al. 2014a) to 30% (Lima et al. 2013) with a median of 2.3 to 2.6%. Note that throughout the results, when a range of annual mortality rates is reported, that corresponds to studies which themselves reported ranges of mortality rates or time intervals, as explained in the methods. Five of the studies of repeated inventories of uneven-aged trees and fourteen of the studies of relatively even-aged planting cohorts reported ranges of mortality rates or time intervals. For the twenty-one studies of relatively even-aged planting cohorts, annual mortality rates ranged from 0.6% (Roman et al. 2015) to 68.5% (Yang and McBride 2003) with a median of 4.4 to 6.5%. For articles that studied planted cohort tree survival in the first five years after planting (sixteen articles), the median annual mortality rate was 6.6 to 7%. Of the literature that studied planted cohort trees past the establishment phase (eight articles), the median annual mortality rate was 2.8 to 3.8%. Notably, the median annual mortality for planted cohort trees older than five years (2.8 to 3.8%), and the median for repeated inventories of uneven-aged trees (2.3 to 2.6%), are both on the high end of the 1 to 3% annual mortality typically reported for mature canopy

**Table 3. Quartiles of annual mortality rates for different tree planting locations. When a given study reported a range of years or a range of mortality values, we used the lower annual mortality value in the "lower" row and the higher annual mortality value in the "higher" row. Studies that did not specify the location or did not examine mortality rates were left out, so the "number of studies" reflects only those used in calculations.**

| Planting location | Number of studies | Lower or higher annual mortality results used | Annual mortality (%) range and quartile | | | | |
|---|---|---|---|---|---|---|---|
| | | | Min. | 1st | Median | 3rd | Max. |
| Street | 20 | lower | 0.00 | 1.59 | 2.54 | 4.60 | 68.47 |
| | | higher | 0.00 | 1.60 | 2.61 | 5.45 | 68.47 |
| Mixed | 14 | lower | 0.00 | 2.22 | 4.30 | 6.77 | 30.00 |
| | | higher | 0.00 | 2.99 | 5.10 | 7.49 | 30.00 |
| Residential yards | 3 | lower | 3.82 | 4.21 | 4.60 | 5.60 | 6.60 |
| | | higher | 3.82 | 4.21 | 4.60 | 5.60 | 6.60 |
| Park | 2 | lower | 1.28 | 1.74 | 2.19 | 2.65 | 3.10 |
| | | higher | 1.28 | 1.74 | 2.19 | 2.65 | 3.10 |

trees in natural forests (e.g., Harcombe and Marks 1983; Condit et al. 1995; Lorimer et al. 2001).

When looking at all of the study designs, annual mortality rates for private residential property yard trees (three studies gave sufficient mortality information) ranged from 3.8% (Ko et al. 2015a) to 6.6% (Roman et al. 2014b) with a median of 4.6%, whereas street tree mortality (twenty studies) ranged from 0% (Nowak 1986 and Roman et al. 2014a) to 68.5% (Yang and McBride 2003) with a median of 2.5 to 2.6% (Table 3). The lower median mortality rate for street trees is noteworthy given the common assumption that street trees face tougher conditions than other types of urban trees (e.g., Moll 1989; Skiera and Moll 1992). Additionally, there were substantially fewer private property studies of yard trees; therefore, understandings of how street and lawn tree mortality compare will improve as further research is conducted.

**Explanations for Exceptionally High and Low Mortality Rates**

Study location and design, as well as the planting program policies, may have had a role in exceptionally high and low mortality rates. For example, Nowak et al. (1990) reported 19% mortality, but the study focused on street trees in a busy transportation corridor in Oakland, CA and noted high rates of vandalism and automobile damage (although these two factors could not be pinpointed as the cause of mortality in their analysis due to limited data). Trees studied by Yang and McBride (2003) in Beijing, China were severely pruned prior to transplanting, likely contributing to the high mortality rate of 68.5%. On the other extreme, as an example of a study with low annual mortality, Koeser et al. (2014) reported 1.31 to 3.25% mortality, but the trees studied were part of a Florida state planting program that replaces trees that die within the first year, and many trees were irrigated,
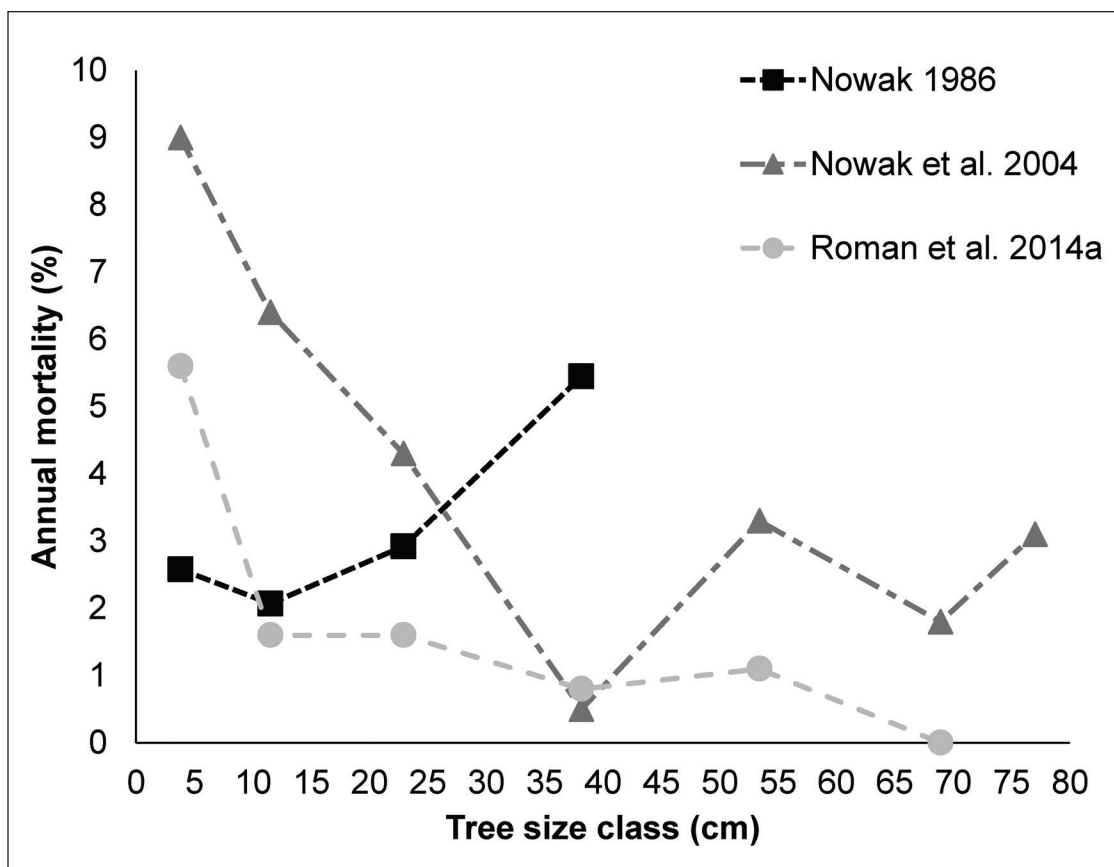


**Figure 3. Mortality curves for studies that provide size-based mortality rates. Annual mortality rates are plotted at the mid-point of the size class interval.**

which may have influenced the resulting low rate. It is important that reviews look carefully at procedures like tree replacement since they might lead to over-stated mortality outcomes, or at the very least mortality rates that are not directly comparable to programs without replacement policies. Roman et al. (2015) reported a low annual mortality rate published for a planting cohort study, 0.6%, for street trees in East Palo Alto, CA. This site was designed by an International Society of Arboriculture Board Certified Master Arborist and had a high level of maintenance, including a drip irrigation system and regular stewardship activities by trained volunteers and paid interns.

## Mortality Curves

A few articles provided enough information for us to graph mortality curves, which illustrate trends in mortality rates over tree size or age (i.e., time since planting). We graphed annual mortality against size classes for the three studies that provided size class–specific mortality rates (Figure 3) and found several distinct patterns. Mortality rates from Nowak's (1986)

study of street trees in Syracuse, NY, display a Type I mortality curve, with higher mortality rates in larger size classes. However, that study differs from the others we assessed. Indeed, other urban tree mortality studies point to Type III or U-shaped mortality curves. In the Nowak et al. (2004) study of randomly located i-Tree Eco plots in Baltimore, MD, we found U-shaped mortality curves, in which mortality was highest for the smallest and largest tree size classes and lower in the middle. The Roman et al. (2014a) study of street trees in Oakland best fits a Type III curve, with highest rates of mortality for the smallest trees. We also graphed reported annual mortality rates against time since planting (i.e., age-based planting cohort mortality) for two studies (Figure 4): New York City street trees (Lu et al. 2010) and Sacramento yard trees (Roman et al. 2016). Both of these studies were similar to a Type III curve. However, these studies only included young trees that had been in the ground fewer than ten years, and planting cohort monitoring studies over longer time periods could show whether the Type III pattern persists or whether a U-shaped curve appears once older trees are included. Based on
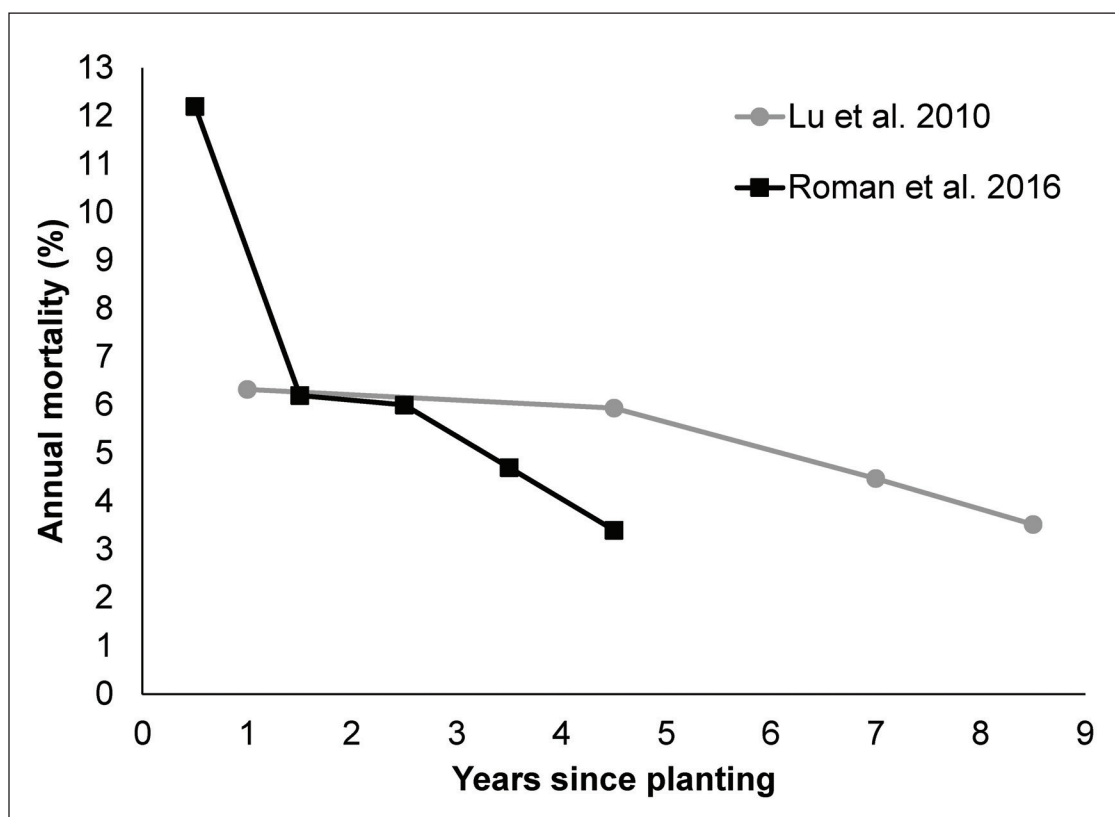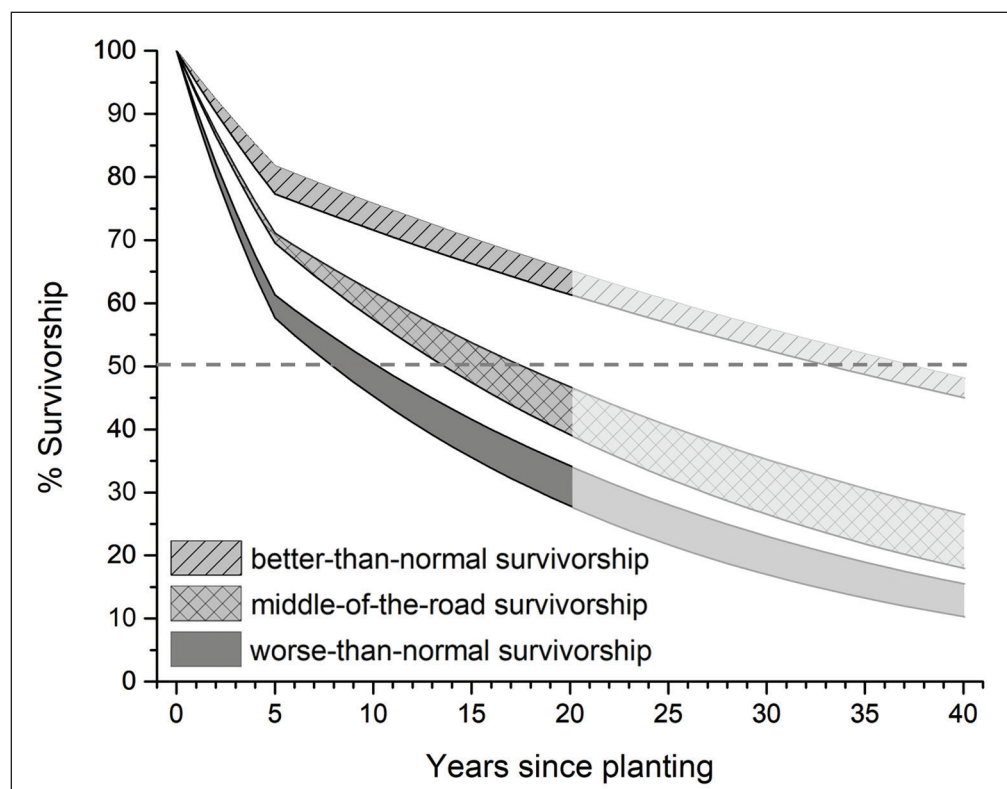


**Figure 4. Mortality curves for studies that provide age-based mortality rates. Annual mortality rates are plotted at the mid-point of the age (i.e., time since planting) interval.**

Figure 5. Survivorship curves based on quartiles of mortality rates in planting cohort studies (Table A1). Better-than-normal survivorship reflects 1st quartile, middle-of-the-road reflects median, and worse-than-normal reflects 3rd quartile. The first five years used establishment mortality rates, while years 6+ used post-establishment rates. The range of values for each curve reflects high and low values for studies that reported a range of mortality rates and/or years. The dashed horizontal line shows 50% survivorship, also known as population half-life. After twenty years, the more transparent grey color reflects the fact that most published planting cohort studies were under twenty years post-planting, therefore post-twenty years annual mortality rates are extrapolations.

these five studies, it would seem that urban trees generally follow either a U-shaped or Type III pattern, similar to trees in natural forests (e.g., Coomes and Allen 2007; Lorimer et al 2001; Metcalf et al. 2009; Lines et al. 2010). Yet more studies reporting mortality rates by age or size class could confirm or refute this generalization, which is admittedly based on just a few studies. It would be helpful if more urban tree mortality studies reported mortality by age or size class to aid in improved understandings of typical mortality curve patterns.

A handful of other studies did not provide explicit data on mortality rates by tree age or size class but still provide interesting information on trends over time. Miller and Miller (1991) provide cumulative percent mortality data for cities in Wisconsin that shows the highest mortality (removals) occurred in the first year, with slightly less mortality in year two, and then mortality stabilized around four years. These data point towards a Type III mortality curve. Ko et al. (2015a) provided a survival curve for twenty-two years of planted yard trees that shows the steepest decline in survivorship between planting and year one, then a steady but less steep decline for the remaining years of observation, suggesting a Type III curve. However,

year one losses in the Ko et al. (2015a) study include trees not planted from a yard tree giveaway program.

While our studies differed too greatly to conduct a true meta-analysis, we were able to graph assumed survivorship curves using age-based life tables we created from the mortality rate quartiles for cohort studies (Figure 5; Table 2 and Appendix Table 4). The first five years used establishment mortality rates, while years 6+ used post-establishment rates. The range of values for each curve reflects high and low values for studies that reported a range of mortality rates and/or years. We graphed better-than-normal, middle-of-the-road, and worse-than-normal survivorship scenarios using 25th percentile, 50th percentile, and 75th percentiles of the annual mortality rates, respectively. The curves (Figure 5) follow a Type III survivorship curve shape due to the nature of the input data which does not include annual mortality rates for very old trees. Life tables and associated survivorship curves like these can provide useful information for practitioners. For example, one could estimate when half the cohort will be dead, known as the population half-life (i.e., 50% survivorship), and create a tree replacement strategy accordingly. For example, the population half-life using the quartile

annual mortality rates from planting cohort studies (Table 2) would be around 7 to 11 years, 13 to 18 years, and 33 to 38 years for worse-than-normal, middle-of-the-road, and better-than-normal survivorship scenarios (Figure 5). It is important to note that these curves are not meant for extrapolation to other cities and planting programs, but rather to display a general trend in the survivorship curves derived from reported mortality rates in the published literature.

## Factors Associated with Mortality

### Quantitative Associations with Mortality for Field-Based Monitoring Studies

The literature cited a variety of statistically significant factors associated with mortality (Table 4 and Appendix Table 3). Of the articles that used field-based monitoring studies and quantitatively examined factors, the most commonly cited biophysical factors were size/age and taxa (e.g., species or cultivar). The most commonly cited human-related factors associated with urban tree death were stewardship, maintenance, and vandalism. Land use and socioeconomic measurements (e.g., net property value, income, and homeownership) were also commonly cited as significant. Trees typically experienced higher mortality when located on properties with unstable homeownership (such as rental, foreclosed, and vacant properties) and when located in neighborhoods with lower incomes and property values. Stewardship and maintenance activities play a positive role in tree survival. Three studies did not find any statistically significant relationships between observed mortality rates and factors examined quantitatively (Thompson et al. 2004; Conway 2016; Martin et al. 2016).

The studies that quantitatively analyzed predictors of mortality share many associated factors, but differ on whether some common factors increase or decrease mortality rates, with sometimes contradictory results. For example, Roman et al. (2014b) associated smaller mature tree size with lower mortality, while Ko et al. (2015a) associated it with a higher mortality when compared to medium-sized mature trees, yet both focus on the same residential lawn tree program in Sacramento. It is unclear why these two studies found different results; other issues related to those taxa or planting sites could be more relevant than mature tree stature. Land use, while cited as statistically significant in many studies (Table 4), does not have a clear mechanism of impact on mortality,

and land use categories may also covary with other important factors. For instance, Nowak et al. (2004) reported high mortality for transportation land use, but this land use had a high prevalence of *Ailanthus altissima,* which the authors speculated might explain that finding. Single-homeowner properties had decreased mortality rates in several studies (Nowak et al. 1990; Lu et al. 2010; Jack-Scott et al. 2013), but the causal explanations for this association are unclear. Various land uses may reflect different planting site conditions and/or maintenance regimes across studies. For example, a tree recorded as single-family residential could alternatively be a yard or street tree, and trees recorded as multi-family residential could be managed by the municipality (such as street trees adjacent to a downtown apartment building) or by landscaping crews hired by an apartment manager (such as lawn trees in a suburban apartment complex). In general, it is not clear whether land use is associated with mortality due to biophysical characteristics of particular land use categories and planting sites, governance of tree stewardship, or some other phenomena.

Most older studies (e.g., Nowak et al. 1990; Miller and Miller 1991) tested for significant influential factors using univariate statistical techniques such as Chi-Square tests, but some more recent studies also relied on univariate techniques (e.g., Nowak et al. 2004; Lu et al. 2010). In contrast, most studies after 2010 (e.g., Staudhammer et al. 2011; Lawrence et al. 2012; Roman et al. 2014a; Koeser et al. 2014; Ko et al. 2015a; Vogt et al. 2015a; van Doorn and McPherson 2018) used more sophisticated multivariate analyses such as logistic regression and non-parametric conditional inference trees. For instance, Roman et al. (2014a) examined the interaction between tree condition and size class using multivariate logistic analysis. When summarizing the papers, no factors stood out as being related to a specific size or life stage in the papers we reviewed, with the possible exception of maintenance or stewardship for recently planted trees.

The prevalence of the most common factors used in quantitative analyses could be due to their relative ease of measurement, since such data can be gathered from planting records, quick field evaluations, and the United States census. Multiple studies followed protocols outlined by the United States Forest Service i-Tree Eco or Forest Inventory and Assessment

**Table 4. Categories of biophysical and human factors associated with mortality based on forty-one papers that provided sufficient information about mortality factors or mechanisms. Within each major category (biophysical or human), factors are listed in order of the frequency with which they appear in the mortality studies reviewed. Studies marked with an (\*) used statistical analysis to quantitatively examine factors (see Appendix Table 3), while unmarked studies examined factors qualitatively (e.g., case studies or surveys of residents). Studies marked with a (‡) examined trees affected by a natural disturbance.**

| Factor | Number of studies | Citations |
| --- | --- | --- |
| **Biophysical factors** | | |
| *Taxa (e.g., genus, species, cultivar)* | 15 | Nowak 1986*; Miller and Miller 1991*; Hauer et al. 1993‡; Duryea et al. 1996*; Duryea 1997‡; Nowak et al. 2004*; Duryea et al. 2007*‡; Lu et al. 2010*; Jack-Scott 2012*; Lawrence et al. 2012*; Koeser et al. 2013*; Lima et al. 2013*; Koeser et al. 2014*; Roman et al. 2015; Boukili et al. 2017* |
| *Size/age* | 13 | Nowak 1986*; Polanin 1991*; Hauer et al. 1993; Duryea et al. 1996*‡; Nowak et al. 2004*; Duryea et al. 2007*‡; Jack-Scott et al. 2013*; Koeser et al. 2013*; Lima et al. 2013*; Roman et al. 2014a*; Roman et al. 2014b*; Ko et al. 2015a*; Morgenroth et al. 2017* |
| *Site characteristics (e.g., planting space, site type, tree density)* | 12 | Jim 2005*; Duryea et al. 2007*‡; Lu et al. 2010*; Staudhammer et al. 2011*; Lawrence et al. 2012; Koeser et al. 2013*; Lima et al. 2013*; Roman et al. 2014a*; Roman et al. 2014b*; Ko et al. 2015a*; Roman et al. 2015; Vogt et al. 2015a* |
| *Condition/vigor/health* | 6 | Nowak 1986*; Hickman et al. 1995*; Nowak et al. 2004*; Koeser et al. 2013*; Roman et al. 2014a*; Roman et al. 2015 |
| *Planting season* | 4 | Miller and Miller 1991*; Roman et al. 2014b*; Ko et al. 2015a*; Vogt et al. 2015a* |
| *Nursery (e.g., source, stock, type, size)* | 3 | Koeser et al. 2014*; Roman et al. 2015; Vogt et al. 2015* |
| **Human factors** | | |
| *Stewardship, maintenance, vandalism* | 15 | Sklar and Ames 1985; Nowak 1986*; Gilbertson and Bradshaw 1985; Struve et al. 1995; Duryea et al. 1996*‡; Sullivan 2005; Boyce 2010*; Lu et al. 2010*; Jack-Scott et al. 2013*; Koeser et al. 2014*; Richardson and Shackleton 2014; Roman et al. 2014b*; Ko et al. 2015a*; Roman et al. 2015; Vogt et al. 2015a* |
| *Socioeconomic measures* | 8 | Gilbertson and Bradshaw 1985; Nowak et al. 1990*; Lu et al. 2010*; Jack-Scott et al. 2013*; Lima et al. 2013*; Roman et al. 2014b*; Ko et al. 2015a*; Vogt et al. 2015a* |
| *Land use* | 6 | Nowak et al. 1990*; Nowak et al. 2004*; Jim 2005*; Lu et al. 2010*; Lawrence et al. 2012*; Steenberg et al. 2017* |
| *Construction and redevelopment activity* | 6 | Nowak 1986*; Miller and Miller 1991*; Hauer 1994*; Koeser et al. 2013*; Steenberg et al. 2017*; Morgenroth et al. 2017* |
| *Infrastructure conflict (e.g., overhead utilities, sidewalks, transportation)* | 5 | Nowak et al. 1990*; Nowak et al. 2004*; Lu et al. 2010*; Jack-Scott 2012*; van Doorn & McPherson 2018* |
| *Landscaping norms and behavior* | 2 | Kirkpatrick et al. 2013; Conway 2016 |

(FIA) systems (Nowak et al. 2004; Staudhammer et al. 2011; Lawrence et al. 2012; Lima et al. 2013; Roman et al. 2014a), which could explain the prevalence of variables like land use (and the specific land use categories observed). While these systems are useful for outlining potential variables to measure, researchers should think critically about which variables are best for their specific mortality studies. For instance, locally-relevant land use and planting site categories could be more informative. Tree health and vigor evaluations, as well as soil characteristics, might be uncommon in urban tree mortality studies because they require more time, training, and equipment to measure. There is ample evidence that soil quality and available soil volume are critical to tree growth and health (e.g., Urban 2008; Rahman et al. 2013; Layman et al. 2016; Scharenbroch et al. 2017). Yet only three of the mortality studies we reviewed (Impens and Delcarte 1979; Lawrence et al. 2013; Koeser et al. 2014) examined soil characteristics in relationship to growth, and none of the studies tested whether soil properties were associated with mortality and survival. Additionally, tree condition and health evaluations are not well-defined and consistently applied (Bond 2010). In terms of human factors influencing mortality, parcel-level ownership data (Roman et al. 2014b; Ko et al. 2015a) and construction or renovation permitting data (Steenberg et al. 2017) show promise for understanding the process of tree mortality, yet these data sets have thus far been rarely applied to statistical modeling of urban tree mortality.

**Qualitative Analyses of Factors Associated with Mortality for Field-Based Monitoring Studies**
Some of the studies that reported mortality data from field-based monitoring studies drew conclusions about influential factors based on qualitative data and observations of trends (e.g., Rhoads et al. 1981; Sklar and Ames 1985; Polanin 1991; Richardson and Shackleton 2014; Roman et al. 2015), and many of these findings complement research with statistical analyses. Rhoads et al. (1981) studied a cohort of street trees in Philadelphia, PA and determined the cumulative survivorship to be approximately 85% for each species, therefore concluding that species is not a significant factor. This study contradicts the many other studies that found taxa to be significant, but the following were in more agreement with the studies that used statistical analysis. Ip (1996) documented

the mortality of a cohort of community-planted trees in the Northwest Region of Canada, gathering information on the cause of mortality or injury to seedlings when they were encountered. Approximately half of the urban and rural projects reported damage to seedlings by people, lawn care equipment, and snowmobiles, so Ip (1996) concluded that smaller tree size could be associated with higher mortality. Sullivan (2004) studied trees planted by a nonprofit in San Francisco, CA, and found that many residents and neighbors cited vandalism as a reason for tree death or removal. Richardson and Shackleton (2014) assessed the condition of newly planted street trees in eleven towns in Eastern Cape, South Africa, in order to understand more about vandalism, finding 42% of recently planted street trees totally snapped, and no difference between snapped trunks for trees with or without protective structures. In a case study of tree planting programs with high survival rates in East Palo Alto and Philadelphia, Roman et al. (2015) concluded that appropriate species selection and planting techniques, small geographic areas, and time-intensive maintenance explained low annual mortality during establishment, ranging from 0.6 to 4.6%. They also found that for the planting project with the lowest published urban tree mortality, East Palo Alto, the few instances of tree deaths were attributed to car accidents and site conditions.

**Other Study Designs**
The aforementioned planting cohort studies (Appendix Table 1) clearly examined changes in a cohort from time of planting to the time of monitoring. Similarly, the repeated inventory studies (Appendix Table 2) examined changes between inventories conducted at two different times. Those are all field-based monitoring that produced mortality data based on analyses of change over time. However, some articles used other study designs and more indirect measures of mortality. We reviewed fourteen studies that made use of data from a single point in time. These studies included surveys of homeowners or other individuals who could provide indirect information about tree mortality, one-time inventories after storms or other major disturbances, and other unique designs. These studies did not have before-and-after data that can be used to estimate rates of loss, but they provide insight into associated factors and are therefore included in the review.

Three of these fourteen studies conducted surveys of individual people in order to learn more about

urban tree mortality. The earliest of these that we found was a study by Beatty and Heckman (1981) in which the authors surveyed urban forest managers responsible for urban forest programs across the United States on the major causes of tree health and survival issues. The most commonly cited issues were lack of water, nutrient deficiency, and vandalism. Some respondents also provided basic mortality information, from which those studies' researchers concluded that larger cities experience higher mortality, while western states and regions with milder climates experience lower mortality. Notably, such conclusions concerning regional mortality trends have not been confirmed or refuted by more recent research. Kirkpatrick et al. (2013) examined residents' attitudes regarding trees in eastern Australia, the amount of removals over the previous five years, and reasons for removals. They found that the main impetus for removal of healthy trees were aesthetic and lifestyle choices. Similarly, Conway (2016) surveyed residents in a suburb of Toronto, Ontario, Canada, to understand motivations for planting and removing trees. The author found that most removals were due to concerns about poor tree health, and the second most common reason was property concerns, both perceived risk and actual damage caused by a tree.

An example of a one-time inventory is the study conducted by Gilbertson and Bradshaw (1985) on trees in northern England. They observed site factors that could have impacted trees, concluding that vandalism (18% of dead trees showed signs) and water and nutrient stress (56% of dead trees showed signs) likely played a role, and that it is possible that the stress from weeds and tie strangulation could have been weakening the trees and predisposing them to vandalism. However, it was not made clear whether these observations were made on standing dead trees or severely impaired trees. Seven studies investigated the effects of natural disasters like storms and earthquakes by conducting one-time inventories following the event. Hauer et al. (1993) conducted an inventory of street tree condition and removals after a major ice storm in Urbana, IL, finding that species, tree form, branch architecture, and the presence/absence of defects all impacted the severity of damage. Jim and Liu (1997) conducted an inventory of trees damaged after a major storm in Guangzhou, China, noting the severity of damage, and found that species, trees size, and development history all influenced storm damage susceptibility. Duryea et al. (1996; 1997; 2007)

combined information from surveys of homeowners and residents along with field visits to properties to assess damage done to trees following eight major hurricanes hitting Florida and Puerto Rico. Those studies concluded that taxa, nativity, wood density, crown density, growth form, pruning, and growing in a cluster were all significantly associated with mortality (Table 4). Earthquake damage to trees was investigated by Morgenroth and Armstrong (2012), who studied removal records of trees in city parks in Christchurch, New Zealand. They found that the removed trees comprised of 9% juvenile, 9% semi-mature, 61% mature, and 21% over-mature treesn and that 88% of all leaning trees were mature or over-mature. Leksungnoen et al. (2017) studied trees in Bangkok, Thailand following severe flooding in 2011. The researchers categorized trees as either flood susceptible (> 50% mortality), tolerant (less than or equal to 50% mortality), or highly tolerant (no mortality after the flood). They found 18% of species to be flood susceptible, 75% tolerant, and 7% highly tolerant.

In addition to survey-based studies and one-time inventories, we found three other unique studies. Polanin (1991) studied a sample of trees that had removal records in Jersey City, NJ, and found that *Platanus × acerifolia* were most often removed due to sidewalk upheaval (i.e., the tree was removed while it was still alive due to infrastructure conflicts), and *Acer platanoides* were more often removed due to death. Helama et al. (2012) conducted a dendrochronology study on Scots pine (*Pinus sylvestris* L.) trees in a park lawn in Helsinki, Finland, in which they concluded that competition from other trees was a likely predisposing factor for mortality and drought as inciting factor. Morgenroth et al. (2017) compared the presence and absence of individual trees before and after earthquake-related demolition to examine removals. Using aerial imagery and field visits, they concluded that 78.4% of the original trees remained after demolition activity.

## Relating Urban Tree Mortality to the Disease-Decline Model

To relate the urban tree mortality literature to the Manion's (1981) disease-decline model, we propose a new framework for urban tree mortality which groups human and biophysical factors as predisposing, inciting, and contributing (Figure 6). Some factors that we listed as inciting might function as
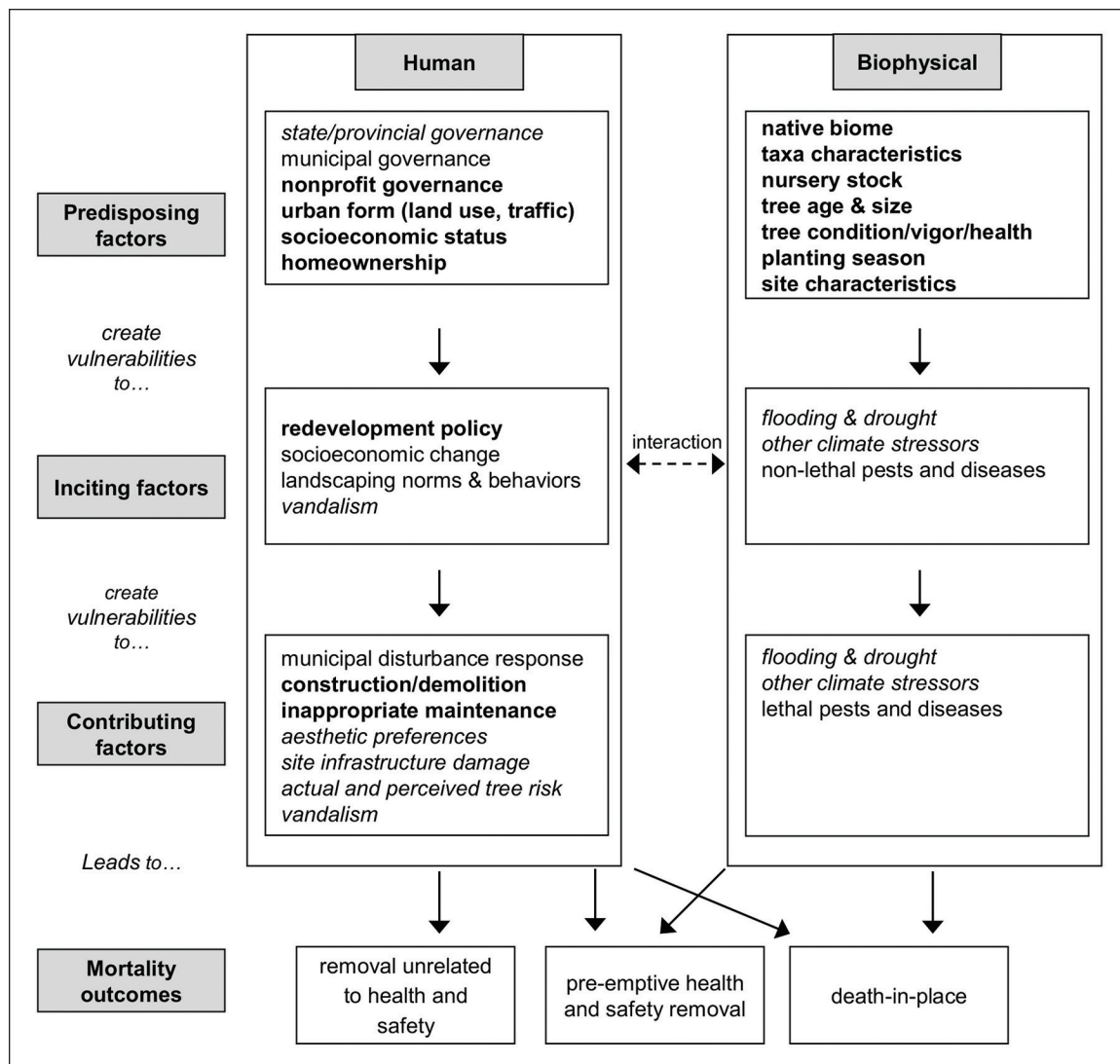
**Figure 6. Urban tree mortality framework outlining predisposing, inciting, and contributing factors. The predisposing and inciting factors create vulnerabilities for trees to die or be removed due to the final contributing factors. Solid one-way arrows indicate that predisposing and inciting factors create vulnerabilities, while contributing factors directly lead to mortality outcomes. The two-way dashed arrow between human and biophysical factors represents interactive effects. Within each text box, factors are ordered from larger scales at the top (e.g., regional, municipal) to smaller scales at the bottom (e.g., parcel, planting site); spatial scale indicates the scale at which the factors could be measured or observed. Factors found to be statistically significant in the studies are bolded, while those that were qualitatively important are italicized.**

contributing factors in certain circumstances, and vice versa, depending on the temporal sequence of stressors (e.g., a tree could be stressed by drought and later killed by a pest, or vice versa). Our framework also orders each set of factors according to spatial scale, from region to planting site. Other authors writing about residential ecosystems (e.g., Roy Chowdhury et al. 2011; Cook et al. 2012; Grove et al. 2015) and urban forest institutions (Mincey et al. 2013) have likewise stressed the importance of multi-scalar

factors. Some of the studies we reviewed noted the spatial scale of the factors they examined (e.g., Roman et al. 2014b; Conway 2016; Morgenroth et al. 2017; Steenberg et al. 2017) but others did not.

Importantly, while conceptual models for tree mortality in natural forests assume that trees die in-place from an accumulation of stresses (Franklin et al. 1987; Das et al. 2007), for urban tree mortality, trees can also be removed while still alive (Figure 7). Such removals can be due to health or risk concerns,

either based on thorough evaluation of the tree or perceived problems (Koeser et al. 2015; Conway 2016; Koeser and Smiley 2017; Klein et al. 2019). Alternatively, removals can be entirely unrelated to health and risk, such as trees removed during construction activities or due to aesthetic preferences (Kirkpatrick et al. 2013; Steenberg et al. 2017). We therefore propose three types of mortality outcomes for urban trees: death-in-place, preemptive removal for tree health and safety reasons, and removal unrelated to health or safety (Figure 6). Biophysical contributing factors, such as hurricanes, lethal pests, and accumulating site stressors, can result in death-in-place or preemptive removals. Human contributing factors can result in any of the three mortality outcome types. For example, mature *Fraxinus* spp. street trees threatened by EAB experience death-in-place if they are not treated with insecticide, and some municipalities are removing untreated *Fraxinus* spp. trees preemptively before the disease hits when they have chosen not to treat (Hauer and Peterson 2017). In another example, site stressors and lack of maintenance can lead to death-in-place for recently planted trees (Roman et al. 2014b; Koeser et al. 2014; Vogt et al. 2015a), but if those mechanisms stress a tree without killing it, preemptive removals could occur because the tree was deemed unhealthy or undesirable. Humans may also make tree removal decisions independent of any health or safety considerations, such as removals due to construction, renovation, and aesthetic preferences (Kirkpatrick et al. 2013; Conway 2016; Steenberg et al. 2017). Notably, while we emphasized earlier that

urban tree mortality studies have typically defined mortality as a combination of trees observed standing dead and removed, the studies we reviewed here were generally not able to differentiate between the three mortality outcome types. During monitoring field work, it is not usually feasible to be certain whether a removed tree was healthy, unhealthy, or dead at the time of removal. Surveys of residents have yielded important information in this regard (Kirkpatrick et al. 2013; Conway 2016), and surveys of municipal arborists might likewise provide insights into the health status of trees at the time of removal.

While this framework builds directly from our review, in that most of the factors listed were statistically significant (bolded in Figure 6) or qualitatively important (italicized in Figure 6) in the studies we reviewed (Table 4; see also Appendix Table 3), there are a few factors listed which were not prominent in our review. For instance, native biome, and the associated precipitation and temperature patterns, is a logical predisposing factor that could relate to species suitability and therefore likelihood of stress and later mortality. This issue was lightly touched upon in a yard tree mortality study in Sacramento (Roman et al. 2014b), where lack of irrigation combined with the seasonal drought in a Mediterranean climate, and species drought tolerance, appeared related to young tree losses, but most studies did not explicitly link biome to mortality since trees within each study were most typically within a single biome. The papers we reviewed also did not raise the issue of landscaping norms and behaviors (an inciting factor in Figure 6),
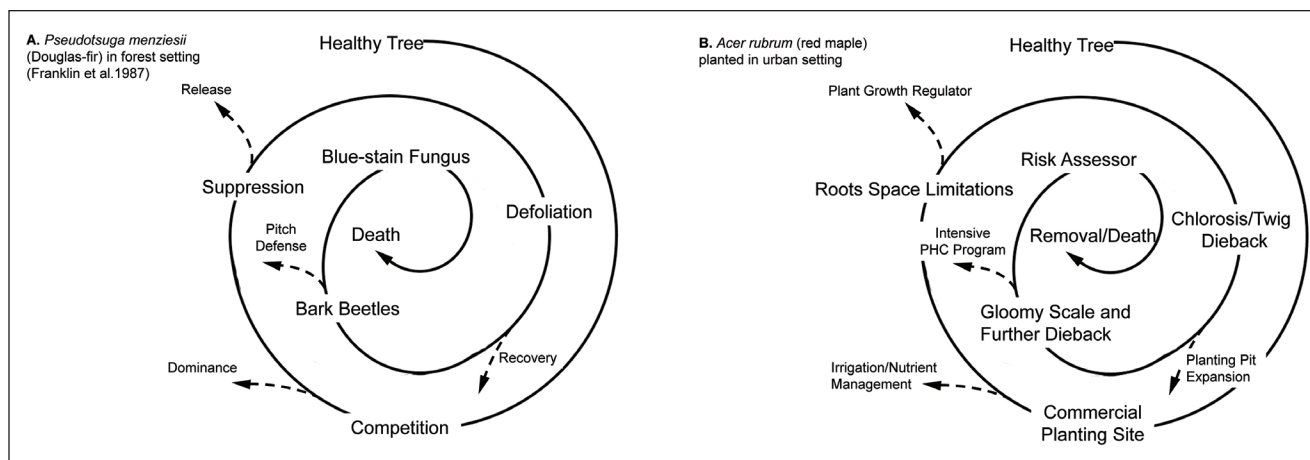


**Figure 7. Tree mortality spirals depicting an example tree in a natural forest (adapted from Franklin et al. 1987) and an example planted urban tree.**

but such behaviors have been studied in the residential ecosystems literature (Cook et al. 2012), and presumably relate to tree maintenance and therefore mortality vulnerability. Other factors listed in Figure 6 which did not come up in our review are pests and diseases, which are widely acknowledged to cause major tree losses, both through death-in-place and preemptive removals based on management responses (Hauer 2012; Kovacs et al. 2014; Sadof et al. 2017). Contemporary and historical examples include *Anoplophora glabripennis* (Asian longhorned beetle, Faccoli and Gatto 2016), *A. planipennis* (EAB, VanNatta et al. 2012; Sadof et al. 2017), *Phytophthora ramorum* (sudden oak death, Rizzo and Garbelotto 2003), and *Ophiostoma ulmi* (Dutch elm disease, Cannon and Worley 1976; Ganley and Bulman 2016). However, this body of literature was not included in our review, therefore the mortality rates summarized in our review (Table 2) do not include catastrophic losses from pests and diseases.

As urban forestry scholars move forward with new lines of tree mortality research, it will be valuable to understand the relative contributions to these various predisposing, inciting, and contributing factors to tree mortality in different regions and programs, and furthermore, to disentangle the processes and interactive effects linking factors together.

### Comparison of Factors Affecting Urban Tree Mortality to the Disease-Decline Model of Tree Death for Non-Urban Trees

Overall, the prevalence of studies citing multiple significant factors for mortality supports the disease-decline model of tree mortality typically applied to non-urban trees (Manion 1981; Franklin 1987; Das et al. 2007). However, the literature we reviewed did not generally tease apart which factors should be considered as pre-disposing, inciting, or contributing (Manion 1981; Franklin 1987), nor did the urban tree mortality literature discuss how causes of or factors associated with tree death and removal vary across age classes (Franklin et al. 1987). One exception is the Helama et al. (2012) publication, a dendrochronology study of trees in an urban park lawn which investigated the disease decline theory and the possible role of competition as a predisposing factor and drought as an inciting factor. The second exception is Boyce's (2010) study of the effect of stewardship on survival for all ages, new trees, and established trees. Additionally, the decline spiral for urban trees may be

cut short by removal of live trees due to perceived or actual risk, construction, or human preference.

## LIMITATIONS

The results of this literature review—and in particular the summarized mortality rates and the factors that influence mortality (Tables 2, 3, 4, Appendix Tables 1, 2, and 3)—are not without limitations. First, our review concentrated on published studies available through online searches. We did not include reports or unpublished data that might be gathered by urban forestry practitioners for internal use, such as repeat street tree inventories conducted for management purposes or monitoring of cohorts to track planted tree survival over time (see Roman et al. [2013] on urban tree monitoring data collection performed by practitioners). Greater insights into mortality trends and processes could be obtained by reaching out directly to urban forest managers for datasets.

Second, this literature review has a relatively limited set of geographies and climates. The bulk of our studies were from the United States (Table 1) and from warm temperate climates with hot or warm summers (Cfa, Csb, as categorized by Kottek et al. 2006) or snowy climates (Dfa; see also Figure 2). It is possible that a larger sample size from many different regions or climates could reveal trends in mortality rates and factors not found in this review.

Third, we are limited in making conclusions about trees planted on various site types. Street trees were the best represented site type in the studies we reviewed. Residential yard tree planting and distribution programs are fairly new (Nguyen et al. 2017), and monitoring yard trees is logistically complicated and time-consuming, as it requires cooperation from numerous private residents. Urban tree mortality research could benefit from further studies of trees in residential yards, other private properties, and landscaped parks; or random plot-based studies could better differentiate between planting site types in addition to land use categories.

Fourth, our review was limited because we assumed a constant rate of mortality when calculating mortality and survivorship percentages from cumulative survival rate data presented in cohort studies, which may not be appropriate for all scenarios (Roman et al. 2016). Recent research integrates concepts from demography into urban forest population studies, drawing attention to limitations like this and offering

suggestions such as data censoring (Roman et al. 2014b; Roman et al. 2016; van Doorn and McPherson 2018). More research needs to be conducted to determine whether constant rates of mortality are realistic and applicable to various urban tree data. For planting cohort mortality studies, we did break-down the annual mortality data into establishment (under five years post-planting) and post-establishment (over five years), however, this is a somewhat arbitrary cut-off. Further research could indicate when the key inflection points are for urban tree survivorship and mortality curves towards better explaining the establishment phase in terms of reduction in annual survival rates (Roman et al. 2014a; Sherman et al. 2016).

Fifth, the studies we reviewed did not examine biophysical factors like soil characteristics and pests, which have been shown to influence tree mortality. Soil characteristics like structure, bulk density, and organic matter content have been shown to influence tree growth and health (Day and Bassuk, 1994; Xiao and McPherson 2011; Grabosky and Bassuk 2016; Scharenbroch et al. 2017). However, most of the urban tree studies that account for these soil differences are experimental plantings, which we did not include in our review. There is also an abundance of urban forestry literature on pests and diseases (e.g., Cannon and Worley 1979; Aukema et al. 2011; Vannatta et al. 2012), but such studies do not generally address rates of mortality or predictive factors, therefore they were not included in our analysis.

Finally, and related to the last point, our results and conclusions are limited to trees planted and managed *in situ,* i.e., in actual urban areas and real-world conditions, as we intentionally excluded experimental planting studies. Though we did find a number in our searches (e.g., Insley 1980; Buckstrup and Bassuk 2000; Gilman 2004; Gerhold 2007; Gerhold 2008; Grabosky and Bassuk 2008; Etemadi et al. 2013; Oldfield et al. 2015; Grabosky and Bassuk 2016), we chose to leave out controlled experimental plantings in order to stay focused on straightforward comparison of mortality rates and factors in real-world conditions. Nonetheless, experimental planting trials can pinpoint both biophysical (e.g., species, cultivar, nursery stock, soil characteristics) and human (e.g., stewardship or maintenance regimes, neighborhood sociodemographic characteristics) factors that observational studies may miss due to confounding variables. For example, studies by Gerhold (1994; 2008) document the performance of different species and

cultivars in urban settings. More recently, McPherson et al. (2018) outlined a method for selecting and evaluating the performance of "climate ready trees" in California. This experimental study and others (e.g., Roloff et al. 2009) provide critical mortality information about new and underutilized urban species within the context of a changing climate. A separate review of mortality rates and factors in experimental plantings could be conducted to illuminate gaps in the literature where future experimental and *in situ* studies could complement each other.

## IMPLICATIONS FOR RESEARCH AND PRACTICE

Despite the limitations described above, this review has some clear implications for research and practice. First and most importantly, for both research and practice, researchers, arborists, and urban forest practitioners should *explicitly define* mortality, survival, and the procedures used to measure and calculate each. Second, not only should definitions be clear, procedures should be *standardized*. The standardization issue has been recently discussed in a primer on urban tree mortality by Roman et al. (2016), an essay on the importance of standardizing at-planting data by Vogt et al. (2015b), and a report on software and data standards for urban tree monitoring by Boyer et al. (2016). Third, methods for calculating and analyzing empirical survival and mortality data from fields like ecology (Woodall et al. 2005; Das et al. 2007; Siccama et al. 2007; van Doorn et al. 2011; Fahey et al. 2013; Cleavitt et al. 2014; Levine et al. 2016) should be applied to urban forest mortality studies to gain a better understanding of population dynamics. Such demographic analytical techniques—like age-based life tables, survivorship and mortality curves, and lifespan metrics—can be applied to urban tree mortality data (Roman et al. 2016).

Fourth, urban forestry programs can benefit greatly by conducting well-designed, long-term monitoring programs that address specific research questions (Lindenmayer and Likens 2010). Variables collected should relate directly to those questions to avoid being "snowed by a blizzard of ecological details" resulting from a "laundry list" of items being monitored (Lindenmayer and Likens 2010).

Finally, a word of caution is warranted about use of the mortality rate ranges presented in this paper. It would be desirable for both researchers and practitioners if the mortality rates summarized in this

review could be used to model urban tree population change over time, for example, in order to project the benefits resulting from planting trees in a particular location (as done in Widney et al. 2016), or predict and plan for urban forest management needs and costs in the future (as suggested by Vogt et al. 2015b; Vogt et al. 2015c). In addition, the survivorship curves (Figure 5) and life tables (Appendix Table 4) provide an example of how population demography approaches can be applied to urban forestry settings in order to maximize management strategies. However, defining and even standardizing calculation methods for mortality rates is insufficient for creating accurate tree population models or scenario-building tools. Instead, we need much more data on urban tree mortality rates in various circumstances—particularly for the under-studied human and biophysical facets of the urban environment: different land use types, socio-economic factors, municipal management strategies, stewardship regimes, types of planting locations, geographies and climates, and pests and diseases (Figure 6).

More long-term mortality studies should be conducted to test for the significance of factors such as soil and microclimate, community and institutional structures (e.g., tree stewardship programs), sociodemographic characteristics, and resident behaviors. Such future studies should focus on both existing and newly planted trees in many different planting sites and include regular monitoring. Municipal tree removal records like those used by Polanin (1991) and Morgenroth and Armstrong (2012) are an underused yet potentially helpful data source for mortality studies. Mixed methods research incorporating both rigorous statistical analysis of predictive factors (both biophysical and human) along with qualitative assessments of communities and institutions would provide a holistic understanding of mortality processes in the anthropogenically constructed urban forest. Further, studies should be conducted to investigate the survival and mortality of large, old trees, perhaps exploring relationships between site and soil characteristics, as well as the role that removal practices and tree protection policies play in creating a population of large, unusually healthy or protected trees. Eventually, with enough data, models could be built to aid in the management of forests in many different cities and scenarios. Given the pace of urban tree mortality research over the past decade, the next

decade will likely be very promising to further advance our understanding of the urban tree mortality process and capacity to build empirically-grounded population projection models.

## CONCLUSION

This review yielded a handful of important take-away points:

- Urban tree mortality studies span a range of quantitative and qualitative study designs, with a dramatic increase in the number of published studies over the past ten years.
- For planting cohort studies, annual mortality tended to be higher during the first five years after planting, aligning with the establishment phase concept.
- Based on mortality rates reported in planting cohort studies, the population half-life for planted urban trees (i.e., when survivorship is 50%) is around 7 to 11 years, 13 to 18 years, and 33 to 38 years for worse-than-normal, middle-of-the-road, and better-than-normal survivorship scenarios.
- The 1st, 2nd, and 3rd quartiles of annual mortality for repeated inventories of uneven-aged trees were more similar to cohort study annual mortality rates of the post-establishment phase (i.e., six or more years after planting) than those of the establishment phase (i.e., first five years after planting).
- Characterizing the factors that influence mortality into categories according to biophysical versus human influences, and predisposing, inciting, and contributing factors (as outlined in Figure 6) is helpful to understanding the urban tree disease-decline spiral.
- Future research could examine topics that are understudied in the current literature, such as microclimate, soil characteristics, institutional structures related to stewardship regimes, parcel-level sociodemographic factors, and resident behaviors.

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**Résumé**. La survie des arbres constitue une mesure de performance pour toute initiative en foresterie urbaine et une compréhension des facteurs qui ont un impact sur la mortalité peut aider les gestionnaires à cibler les ressources et améliorer leur survie. En outre, les investissements pour la plantation d'arbres urbains ont comme prémisse la survie des arbres afin de maximiser les services écosystémiques attendus. Dans cette revue de littérature, nous avons classé en catégories les facteurs fréquemment associés avec la mortalité des arbres urbains et fait un résumé du taux de mortalité publié dans 56 recherches mettant l'accent sur les études portant sur les arbres d'alignement, ceux dans les cours ainsi que dans les parcs aménagés. Les plans d'étude incluaient le suivi quantitatif sur le terrain de populations d'arbres d'âges différents et l'observation de cohortes d'arbres d'âge uniforme, aussi bien que des analyses qualitatives. Le taux de mortalité annuelle s'élevait à 0.6% à 68.5% pour les études de cohortes et de 0% à 30% pour celles portant sur les populations d'arbres aux âges variés. Les premiers, deuxième et troisième quartiles de mortalité annuelle étaient de 2.8% à 3.8%, de 4.4% à 6.5% et de 7.1% à 9.3% pour les cohortes d'âge uniforme tandis que pour les populations d'âges variés, ils étaient de 1.6%, 2.3% à 2.6% et de 3.0% à 3.3% (ces fourchettes reflètent les études qui signalaient une variation pour le période de temps ou le taux de mortalité). Pour les études de cohorte, la mortalité annuelle tendait à être la plus haute au cours des cinq premières années suivant la plantation. Les facteurs biophysiques les plus couramment mentionnés en association avec la mortalité furent les taxons (15 articles), la dimension ou l'âge des arbres (13 articles) et les caractéristiques du site (12 articles). Les facteurs d'origine humaine les plus couramment mentionnés furent la gestion, l'entretien et le vandalisme (15 articles). Davantage d'études à long terme sont nécessaires afin d'investiguer sur l'influence des caractéristiques du site sur la mortalité, incluant l'examen (rarement pratiqué) du sol et les caractéristique du microclimat. Les futures recherches devraient également examiner les structures institutionnelles en lien avec les résultats en matière de mortalité, aussi bien qu'avec les facteurs des groupes sociodémographiques et les comportements des résidents.

**Zusammenfassung.** Das Überleben von Bäumen ist ein Leistungsmaß für urbane Forstinitiativen und ein Verständnis der Faktoren, die die Sterblichkeit beeinflussen, kann den Verantwortlichen helfen, Ressourcen anzusteuern und das Überleben zu verbessern. Darüber hinaus hängen die Investitionen der Baumpflanzung vom Überleben der Bäume ab, um deren Ökosystemleistungen zu maximieren. In dieser Literaturübersicht haben wir Faktoren kategorisiert, die gewöhnlich mit der Sterblichkeit von Straßenbäumen assoziiert werden und die Sterblichkeitsraten, wie sie in 56 Studien publiziert wurden zusammengefasst. Dabei lag der Fokus auf Bäumen entlang von Straßen, in Gärten und Landschaftsparkanlagen. Die Studienkonzepte enthielten quantitative Felderhebungen von Baumpopulationen unterschiedlichen Alters und ein Tracking von gleich alten Baumgruppen, genauso wie eine qualitative Analyse. Die annuellen Sterberaten rangierten von 0.6% bis 68.5% bei Jahrgangsbäumen und 0% bis 30% für wiederholte Inventuren von Bäumen ungleichen Alters. Das erste, zweite und dritte Quartil der jährlichen Sterblichkeit war 2.8% bis 3.8%, 4.4% bis 6.5% und 7.1% bis 9.3% für Jahrgangsgruppen; und 1.6%, 2.3% bis 2.6%, und 3.0% bis 3.3% für wiederholte Inventuren von Bäumen ungleichen Alters (die Spannen reflektieren Studien, die diese Spannen über die Zeitperiode oder die Sterblichkeitsrate berichten). Bei den Jahrgangsstudien schien die annuelle Sterblichkeit währen der ersten fünf Jahre nach der Verpflanzung am höchsten zu sein. Die meistzitierten biophysikalischen, mit der Sterblichkeit assoziierten Faktoren waren Taxa (15 Artikel), Baumgröße/-alter (13 Artikel) und Standortbedingungen (12 Artikel). Die meistzitierten, mit menschlichem Einfluss verbundenen Faktoren waren Patenschaften, Erhaltung und Vandalismus (15 Artikel). Es werden mehr Langzeitstudien gebraucht, um zu untersuchen, wie sehr die Standortbedingungen die Sterblichkeit beeinflussen, einschließlich der selten untersuchten Boden- und Mikroklimacharakteristika. Künftige Forschung sollte neben soziodemographischen Faktoren und Anwohnerverhalten auch institutionelle Strukturen in Verbindung mit der Mortalität beinhalten.

**Resumen.** La supervivencia de los árboles es una medida de rendimiento para las iniciativas de silvicultura urbana, y una comprensión de los factores que influyen en la mortalidad puede ayudar a los administradores a orientar los recursos y mejorar la supervivencia. Además, las inversiones en plantación de árboles dependen de su supervivencia para maximizar los servicios de los ecosistemas. En esta revisión de la literatura, clasificamos los factores comúnmente asociados con la mortalidad de árboles y resumimos las tasas de mortalidad publicadas en 56 estudios, centrándonos en los estudios de árboles a lo largo de las calles, en los patios y en los parques paisajísticos. Los diseños de los estudios incluyeron el monitoreo de campo cuantitativo de poblaciones de árboles de edad irregular y el seguimiento de las cohortes de plantación de árboles de edad igual, así como análisis cualitativos. Las tasas de mortalidad anual oscilaron entre el 0.6% y el 68.5% para los estudios de cohortes y entre el 0% y el 30% para los inventarios repetidos de árboles de edad irregular. El primer, segundo y tercer cuartil de mortalidad anual fue 2.8% a 3.8%, 4.4% a 6.5%, y 7.1% a 9.3% para las cohortes de plantación, y 1.6%, 2.3% a 2.6% y 3.0% a 3.3% para inventarios repetidos de árboles de edad irregular (los rangos reflejan estudios que informaron un rango para el período de tiempo o la tasa de mortalidad). Para los estudios de cohortes, la mortalidad anual tendió a ser más alta durante los primeros cinco años después de la plantación. Los factores biofísicos más comúnmente citados asociados con la mortalidad fueron los taxones (15 artículos), el tamaño y la edad de los árboles (13 artículos) y las características del sitio (12 artículos). Los factores relacionados con los humanos más comúnmente citados fueron la administración, el mantenimiento y el vandalismo (15 artículos). Se necesitan más estudios a largo plazo para investigar cómo las características del sitio influyen en la mortalidad, incluidas las características del suelo y el microclima rara vez examinadas. Las investigaciones futuras también deben examinar las estructuras institucionales relacionadas con los resultados de mortalidad, así como los factores sociodemográficos a nivel de parcela y los comportamientos de los residentes.

## Appendix Table 1. Urban tree mortality rates for planting cohort monitoring studies.

**Time period *t* is years since planting. Rates were reported directly in the studies, except those with †, which were calculated using data provided in the study. When a range of mortality and time periods were reported, the maximum and minimum values were used in calculations. Cohort studies that provided a range for time since planting are considered multi-year cohorts.**

| Citation | Location (City and state) | Sample type(s) and sample size ($n_o$) | Time $t$ (yrs) | Annual mortality $q_{annual}$ (%) [cumulative survivorship $l_t$ (%)] | Study notes |
|---|---|---|---|---|---|
| Impens and Delcarte (1979) | Brussels, Belgium | Street trees<br>1974 (2300)<br>1975 (3710)<br>1976 (3148)<br>1977 (2463) | 1 | 6.5 [93.5†]<br>10.3 [89.7†]<br>19.7 [80.3†]<br>8.7 [91.4†] | Mix of species. Newly planted and inventoried one year after stated planting year. |
| Rhoads et al. (1981) | Philadelphia, PA | Street trees (unk.) | 14 | 1.2† [85] | |
| Nowak et al. (1990) | Oakland/Berkeley, CA | Street trees (480) | 2 | 19 [66†] | Paper also provides mortality rates by species. |
| Miller and Miller (1991) | WI<br>Milwaukee, redeveloped<br>Milwaukee, not redeveloped<br>Stevens Point<br>Waukesha | Street trees<br>(311)<br>(692)<br><br>(368)<br>(677) | 4-6<br>4-6<br><br>4-9<br>4 | 10.4-15.8†<br>[51.8]<br>7.7-11.3† [62]<br><br>3.2-7.0† [74.9]<br>6.5† [76.5] | |
| Struve et al. (1995) | Multiple communities, OH | Curb lawn and lawn trees | 2-3 | 7.2-10.6† [80] | Paper also provides mortality rates by species and city. |
| Ip (1996) | Northwest Region, Canada | Mixed<br>1 yr. old<br>2 yrs. old<br>3 yrs. old | <br>1<br>2<br>3 | <br>10 [90†]<br>6.7 [87†]<br>2.7 [92†] | Includes urban, rural, and agricultural trees. |
| Sullivan (2004) | San Francisco, CA | Street trees<br>(1987)<br>(1869) | <br>5<br>10 | <br>2.9† [86.5]<br>3.8† [67. 9] | |
| Thompson et al. (2004) | IA, 21 communities | Trees in streets, parks, schoolyards (932) | 2-6 | 6 [91] | Average annual mortality rate reported by source was 6%. |
| Gates and Lubar (2007) | Philadelphia, PA | Trees in parks and streets, all species (1326) | 1-2 | 3.9-7.7† [92.3†] | |
| Boyce (2010) | New York City, NY | Street trees in pits<br>With stewardship<br>Without stewardship | ≤ 4 | <br>1.25<br>4.17 | |

| Citation | Location (City and state) | Sample type(s) and sample size ($n_o$) | Time $t$ (yrs) | Annual mortality $q_{annual}$ (%) [cumulative survivorship $l_t$ (%)] | Study notes |
|---|---|---|---|---|---|
| Lu et al. (2010) | New York City, NY | Street trees<br>Total (13,405)<br>3-6 yrs. cohort (2417)<br>6-8 yrs. cohort (2417)<br>8-9 yrs. cohort (5935) | 3-9<br>3-6<br>6-8<br>8-9 | 3.2-9.4[†] [74.3]<br>4.0-7.9[†] [78.2]<br>3.9-5.1[†] [73]<br>3.3-3.7[†] [73.8] | |
| Roman and Scatena (2011) | Philadelphia, PA | Street trees (151) | 2-10 | 2.4-11.2 [78.8[†]] | Paper also provides survivorship for different planting years, each being its own cohort. |
| Koeser et al. (2013) | Milwaukee, WI | Street trees,<br>0-10 yrs. (793)<br>  No construction (391)<br>  Construction (402)<br>11-25 yrs. (895)<br>  No construction (686)<br>  Construction (219) | 10<br><br><br>16 | 1.8[†] [83.6]<br>2.5[†] [77.9]<br>1.3[†] [81.1]<br>1.2[†] [82.6] | |
| Koeser et al. (2014) | FL, various cities | Trees in parking lots, highways, streets, lawns, parks (2354) | 2-5 | 1.3-3.3[†] [93.6] | Paper also provides survivorship by species. |
| McPherson (2014) | Los Angeles, CA | street trees (84)<br>park trees (225)<br>yard trees (70) | 4-5<br>3.1 [90.7]<br>4.6 [77.1] | 4.4 [79.8] | |
| Roman et al. (2014b) | Sacramento, CA | Single-family residential yard trees (370) | 5 | 6.6 [70.9] | |
| Ko et al. (2015a) | Sacramento, CA | Lawn trees (317) | 22 | 3.8 [42.4] | 22-year post-plantin survivorship was 42.4%, taken from survival curve. Proportion of trees surviving out of those actually delivered was 35.3%. |
| Roman et al. (2015) | East Palo Alto, CA<br>Philadelphia, PA<br>Philadelphia, PA | Street trees<br>(568)<br>(150)<br>(94) | 5.92<br>6.25<br>6.58 | 0.6 [96.3]<br>1.6 [90.7]<br>4.6 [73.4] | |
| Vogt et al. (2015) | Indianapolis, IN | Community planted street trees (1345) | 2-6 | 1.9-5.5[†] [89.4] | |
| Widney et al. (2016) | Detroit, MI<br>Indianapolis, IN<br>Philadelphia, PA | Street trees (4059) | 3-5 | 7 [79]<br>7 [80]<br>13 [59] | Authors used half-years to designate the difference between fall and spring plantings. |
| Yang and McBride (2003) | Beijing, China | Street trees | 11 wks. | 68.5[†] [75[†]] | Severely pruned prior to transplanting. |

## Appendix Table 2. Urban tree mortality rates for repeated inventory studies of uneven-aged trees.

**Time period *t* is years since planting. Rates were reported directly in the studies, except those with †, which were calculated using data provided in the study. When a range of mortality and time periods were reported, the maximum and minimum values were used in calculations.**

| Citation | City and state | Sample type(s) and sample size ($n_o$) | Time $t$ (yrs) | Annual mortality $q_{annual}$ (%) | Study notes |
|---|---|---|---|---|---|
| Impens and Delcarte (1979) | Brussels, Belgium | Street trees<br>1974 (75,653)<br>1975 (80,493)<br>1976 (82,374)<br>1977 (81,581) | 1 | 2.8<br>2.6<br>3.3<br>1.9 | |
| Dawson and | Urbana, IL | Street trees (1768) | 50 | 1.1 | |
| Nowak (1986) | Syracuse, NY<br>Syracuse and Rochester, NY | Street trees (1454)<br>Street trees (1160) | 7<br>9 | 2.4†<br>2.3† | Paper also provides mortality rates for species, dbh, curbing, strip width, situation, adjacent land use, utilities, crown, ground disturbance, and condition. |
| Miller and Neely (1993) | Champaign, IL | Street trees, campus and city parkways (98) | 5 | 1.5† | Trenched in 1987, annual growth and mortality data collected through 1991. |
| Hauer et al. (1994) | Milwaukee, WI | Street trees | 10 | 2.3 | Compared survival of street trees damaged by construction to those not damaged during 1981-1985. |
| Hickman et al. | Lodi, CA | Park trees (695) | 7 | 1.28 | |
| Nowak et al. (2004) | Baltimore, MD | All trees (1396)<br>Transportation (33)<br>Commercial/<br>  industrial (15)<br>Urban open (228)<br>High density<br>  residential (77)<br>Forest (728)<br>Low-medium density<br>  residential (136)<br>Institutional (4)<br>Barren (7) | 2 | 6.6<br>20.2<br>10.6<br>8.2<br>6.0<br>5.9<br>2.2<br><br>0<br>0 | Paper also provides mortality for dbh class, condition, and species. |
| Jim (2005) | Hong Kong, China | Heritage trees in parks | 10 | 1.5† | Performed post-mortem assessments to explain possible relationships between predisposing factors and eventual tree loss. |
| Boyce (2010) | New York City, NY | Street trees in pits<br>  With stewardship<br>  Without stewardship | > 4 | <br>0.49<br>1.9 | Paper also provides mortality rates for new and established trees based on growing season. |

| Citation | City and state | Sample type(s) and sample size ($n_o$) | Time $t$ (yrs) | Annual mortality $q_{annual}$ (%) | Study notes |
|---|---|---|---|---|---|
| Staudhammer et al. (2011) | Houston, TX | All trees (305) | 8 | 4.7 | Paper also provides mortality rates for different size classes and a graph of average hurricane-related and non-hurricane mortality rates for these land use categories: developed low intensity, developed high intensity, developed open, woody wetlands. |
| Lawrence et al. (2012) | Gainesville, FL | All trees (754) Commercial Forest Institutional Residential | 3-4 | 9.97 3.12 5.41 19.2 9.12 | |
| Jack-Scot et al. (2013) | New Haven, CT | Community planted trees | 4-16 | 1.9-7.3[†] | |
| Lima et al. (2013) | San Juan, Puerto Rico | All trees (244) | 9 | 30 | Paper provides a graph of average annual plot-level mortality rates for these land use categories: commercial/industry/institution/ transportation, residential, vacant, mangrove forest, upland secondary forest. |
| Roman et al. (2014a) | Oakland, CA | Street trees (995) | 5 | 3.7 | |
| Escobedo et al. (2016) | Santiago, Chile | Urban trees in inventory plots Broadleaf-deciduous (476) Broadleaf-evergreen (210) Conifer (43) Palm (20) | 12 | 2.99 2.98 3.29 2.92 | Inventory of plots on different land use classes: residential, commercial/ industrial, green areas, agriculture, transportation. |
| Martin et al. (2016) | San Francisco, CA | Street trees *Arbutus* (135) *P. cerasifera* (136) *P. serrulata* (122) | 17-2 2 | 1.2-1.5[†] 1.1-1.5[†] 2.0-2.6[†] | |
| Boukili et al. (2017) | Cambridge, MA | Street trees (592) | 3 | 3.6 | This is the citywide annual mortality. Average street segment mortality is 6.7%. |
| Steenberg et al. (2018) | Toronto, Canada | Yard, street, public ROW (806) | 6-7 | 2.6-3.0[†] | |
| van Doorn and McPherson (2018) | Claremont, CA | Street, 21 species (community-level) (732) | 14 | 1.03 | The stated 1.03% is the "community-level median removal rate." |

## Appendix Table 3. Statistically significant factors associated with mortality.

**Results from cohort monitoring studies (C), repeated inventories (RI), and other study designs (O) that qualitatively examined associated factors. Time period _t_ is years since planting. Factors followed by (+) had a positive correlation with survival. Factors followed by (–) had a negative correlation with survival. Factors followed by (/) were examined, but a nonsignificant relationship with survival was observed. Factors followed by (varies) had a more complex relationship (e.g., mortality differences for three or more species).**

| Citation | Location (City and state) | Sample type(s) and sample size ($n_o$) | Time $t$ (yrs) | Significant factors |
|---|---|---|---|---|
| Gilbertson and Bradshaw (1985)[O] | England, multiple communities | N/A (10,000) | N/A "newly planted" | **Human** – Larger town size (–), new town (+) |
| Hickman et al. (1995)[RI] | Lodi, CA | Park trees (695) | 7 | **Biophysical** – Decline (–), trunk vigor (+), lean (–); higher risk rating for soil (/), wind (/), root (/), and butt (/) **Human** – Irrigation frequency (/) |
| Nowak (1986)[RI] | Syracuse, NY | Street trees (1454) | 7 | **Biophysical** – Total sample: _Acer saccharum_ (–), _Acer platanoides_ (+), strip width (/) **Human** – Total sample: curbing (/), type of utility wires (/), adjacent land use (/) |
|  | Syracuse and | Street trees (1160) | 9 | **Biophysical** – Total sample: crown closure on 3 sides (+); _Acer platanoides_: decline class 1.0 (+), class 2-5 (–) **Human** – All maples: pruning (–); _Acer platanoides_: 1976 ground disturbance (–) |
| Nowak et al. (1990)[C] | Oakland/ Berkeley, CA | Street trees (480) | 2 | **Human** – Apartments (–), public greenspace (–), single family residence (+), subway station (+), unemployment rate (–) |
| Miller and Miller (1991)[C] | WI     Milwaukee, redeveloped     Milwaukee, not redeveloped     Stevens Point     Waukesha | Street trees (311)   (692)   (368) (677) | 4-6  4-6  4-9 4 | **Biophysical** – Taxa (varied), planted in fall season (+) (Waukesha only) **Human** – Redeveloped area (–) vs. non-redeveloped area (+) |
| Hauer et al. (1994)[RI] | Milwaukee, WI    Construction damage    No construction damage | Street trees (432) (413) | 10 | **Human** – Construction (–) |
| Duryea et al. (1996)[O] |  | Trees on streets and in yards after storm (18,200) | N/A | **Biophysical** – Taxa (varies), nativity (+), size within species group (varies) **Human** – Pruning (varies) |
| Nowak et al. (2004)[RI] | Baltimore, MD | Trees within various land use classes (1396) | 2 | **Biophysical** – _Morus alba, Ailanthus altissima, Cornus florida, Acer negudo_ (–),  dbh class of 0-7.6 cm (–) and 30.6-45.7 cm (+), tree condition of poor, critical, or dying (–), tree condition of excellent (–) **Human** – Transportation (–), low-med. residential (+) |

| Citation | Location (City and state) | Sample type(s) and sample size ($n_o$) | Time $t$ (yrs) | Significant factors |
|---|---|---|---|---|
| Thompson et al. (2004)[C] | IA, 21 communities | Trees in streets, parks, school-yards (932) | 2-6 | **Biophysical** – Taxa (/)<br>**Human** – Quadrant (/), community size (/), project site location (/) |
| Jim (2005)[RI] | Hong Kong, China | Heritage trees in parks and roadsides (380) | 10 | **Biophysical** – Public greenspace habitat[2] (–), roadside (–)<br>**Human** – Open space (–), government (–), institutional (–), community (–) |
| Duryea et al. (2007)[O] | FL, various cities | Trees on streets and in yards after storm (18,200) | N/A | **Biophysical** – Taxa (varies), nativity (/), wood density (+), crown density (+), decurrent growth form (+), growing in cluster (+) |
| Boyce (2010)[C,RI] | New York City, NY | Street trees in pits<br>  With stewardship<br>  Without stewardship | ≤ 4 (mixed-aged cohort)<br>> 4 (repeated inventory) | **Human** – Stewardship (+) |
| Lu et al. (2010)[C] | New York, NY | Street trees<br>Total (13,405)<br>3-6 yrs. cohort (2417)<br>6-8 yrs. cohort (5053)<br>8-9 yrs. cohort (5935) | <br>3-9<br>3-6<br><br>6-8<br><br>8-9 | **Biophysical** – Taxa: *Pyrus calleryana* (+)<br>**Human** – Industrial (–), open space (–), vacant (–), one- and two-family residential (+), stewardship index (+), low traffic area (+), tree pit enhancement (+) |
| Staudhammer et al. (2011)[RI] | Houston, TX | Trees within various land use classes[1] (305) | 8 | **Biophysical** – Tree density (–), hurricane (–), developed open space (–), developed high-density (–) |
| Jack-Scott (2012)[C] | Philadelphia, PA | Community planted trees | ~1-5 | **Biophysical** – Taxa: *P. virginiana* and *Platanus × acerifolia* (+), *C. canadensis* (–)<br>**Human** – Street traffic intensity (–) |
| Lawrence et al. (2012)[RI] | Gainesville, FL | Various land use classes (754) | 3-4 | **Biophysical** – Tree density (–), *Quercus nigra* and *Q. laurifolia* (–)<br>**Human** – Institutional (–), commercial (+) |
| Jack-Scott et al. (2013)[RI] | New Haven, CT | Community planted trees (1393) | 4-16 | **Biophysical** – Tree age (–)<br>**Human** – Percent homeownership (varies), group experience (+), group longevity (+), group size (varies), group type (varies) |

## Appendix Table 3. (continued)

| Citation | Location (City and state) | Sample type(s) and sample size ($n_o$) | Time $t$ (yrs) | Significant factors |
|---|---|---|---|---|
| Koeser et al. (2013)[C] | Milwaukee, WI | Street trees, 0-10 yrs. (793) No construction (391) Construction (402) 11-25 yrs. (895) No construction (686) Construction (219) | 10<br><br><br>16 | **Biophysical** – Taxa: *Gleditsia triacanthos* (+), *Acer saccharum* (−), trunk diameter (−), planting space width (+), tree condition (+)<br>**Human** – Adjacent to construction (−) |
| Lima et al. (2013)[RI] | San Juan, Puerto Rico | Various land use classes (244) | 9 | **Biophysical** – Species nativity (varies), grass cover (+), species height, dbh, and CLE value (+), street tree (−), forested plots (+)<br>**Human** – Higher income neighborhoods (+), higher neighborhood population (−) |
| Koeser et al. (2014)[C] | FL, various cities | Trees in parking lots, highways, streets, lawns, parks (2354) | 2-5 | **Biophysical** – Nursery stock: irrigated container-grown trees (+), taxa (varies)<br>**Human** – In-ground irrigation (+) |
| Roman et al. (2014a)[RI] | Oakland, VA | Street trees (995) | 5 | **Biophysical** – Larger tree dbh (+), better foliage health rating (+) (for smallest size class), planted in sidewalk cut-out (vs. strip) (+) |
| Roman et al. (2014b)[C] | Sacramento, CA | Single-family residential yard trees (370) | 5 | **Biophysical** – Species water use demand (−), planted in front yard (+), planted in rainy season (+), mature tree size (−), days since planting (−)<br>**Human** – Homeowner stability (+), maintenance rating (+), number of trees delivered (−), neighborhood income (varies), neighborhood educ. attainment (+) |
| Ko et al. (2015a)[C] | Sacramento, CA | Lawn trees (317) | 22 | **Biophysical** – Planted in backyard (−), small mature tree size (−), planted in rainy season (−)<br>**Human** – Highest and lowest net property values (−), unstable homeownership (−), number of trees delivered (−) |
| Vogt et al. (2015a)[C] | Indianapolis, IN | Community planted street trees (1345) | 3-6 | **Biophysical** – Number of trees planted in project (−), fall planting season (−), percent impervious surface (−), planting year (+), nursery 3 (varies)<br>**Human** – Median household income ($1000) (+), percent renter occupied homes (+), percent moved in last 5 years (+), watering strategy (varies), watering strategy × fall planting (−) |
| Conway (2016)[O] | Mississauga, Canada | Survey of residents | N/A | **Human** – Neighborhood (/), length of residency (/), ownership status (/), university education (/), resident age (/), income (/), ethnicity (/) |

| Citation | Location (City and state) | Sample type(s) and sample size ($n_o$) | Time $t$ (yrs) | Significant factors |
|---|---|---|---|---|
| Martin et al. (2016)[RI] | San Francisco, CA | Street trees on right-of-way | 17-22 | **Biophysical** – Tree health (/), tree age (/), microclimate (/) |
| Boukili et al. (2017)[RI] | Cambridge, MA | Street trees (592) | 3 | **Biophysical** – *A. platanoides, A. rubrum*, and *T. cordata* (+), initial tree diameter (/), percent permeable surface (/), growing season solar insolation (/) **Human** – Street segment (/) |
| Morgenroth et al. (2017)[O] | Christchurch, New Zealand | Mixed land use classes (1209) | n/a | **Biophysical** – Small trees (–), small trees closer than 0.7 m to demolished building (–), large trees closer than 20 m to driveway (–) |
| Steenberg et al. (2017)[RI] | Toronto, Canada | Yard, street, public ROW (806) | 6-7 | **Human** – Presence and number of building permits (–), multi-unit housing (street-level scale) (–) |
| van Doorn and McPherson (2018)[RI] | Claremont, CA | Street trees, 21 species (community-level) (732) | 14 | **Biophysical** – Tree size (/), tree condition (/), growing space (/) **Human** – Presence of overhead utility lines (+), sidewalk damage (/) |

[1]*Staudhammer et al. (2011) conceptualize "developed open space" and "developed high-density" as "land use" categories, but for the purposes of consistency here, we consider these to be biophysical descriptions of the site (i.e., "Site characteristics" in Table 3 in the main text).*

[2]*Jim (2005) uses "public greenspace" to describe the planting habitat, which is biophysical in nature. Others (e.g., Nowak et al. 1990) use this term to describe a human-related land use category. We acknowledge discrepancies between terminologies and how authors used them, but chose to keep the wording for factors and their categorization the same as the original publication in order to best summarize the literature.*

## Appendix Table 4. Life table based on the mortality rates of planting cohort monitoring studies.

The worse-than-normal survivorship column uses the 75th percentile annual mortality rates, the middle-of-the-road survivorship column uses the 50th percentile values, and the better-than-normal survivorship column uses the 25th percentile values. When studies provided a range for the time period, we used the lower value and higher values of time to calculate the lower and higher mortality rates, respectively. The first five years used establishment mortality rates, while years 6+ used post-establishment rates. Approximate population half-lives are **bolded**.

| Years since planting | Better-than-normal survivorship | | Middle-of-the-road survivorship | | Worse-than-normal survivorship | |
|---|---|---|---|---|---|---|
| | **Lower** | **Higher** | **Lower** | **Higher** | **Lower** | **Higher** |
| 0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1 | 96.0 | 95.0 | 93.4 | 93.0 | 90.7 | 89.6 |
| 2 | 92.2 | 90.2 | 87.2 | 86.5 | 82.2 | 80.2 |
| 3 | 88.6 | 85.7 | 81.5 | 80.4 | 74.6 | 71.9 |
| 4 | 85.1 | 81.4 | 76.1 | 74.8 | 67.6 | 64.4 |
| 5 | 81.7 | 77.3 | 71.1 | 69.6 | 61.3 | 57.7 |
| 6 | 80.5 | 76.1 | 69.1 | 67.0 | 59.0 | 54.9 |
| 7 | 79.3 | 75.0 | 67.2 | 64.4 | 56.7 | **52.3** |
| 8 | 78.1 | 73.8 | 65.4 | 62.0 | 54.6 | **49.9** |
| 9 | 76.9 | 72.7 | 63.6 | 59.7 | 52.5 | 47.5 |
| 10 | 75.8 | 71.6 | 61.8 | 57.4 | **50.5** | 45.3 |
| 11 | 74.6 | 70.5 | 60.1 | 55.3 | **48.6** | 43.1 |
| 12 | 73.5 | 69.4 | 58.5 | 53.2 | 46.7 | 41.1 |
| 13 | 72.4 | 68.4 | 56.8 | **51.2** | 44.9 | 39.1 |
| 14 | 71.3 | 67.3 | 55.3 | **49.3** | 43.2 | 37.3 |
| 15 | 70.3 | 66.3 | 53.8 | 47.4 | 41.6 | 35.5 |
| 16 | 69.2 | 65.3 | 52.3 | 45.6 | 40.0 | 33.9 |
| 17 | 68.2 | 64.3 | **50.8** | 43.9 | 38.5 | 32.3 |
| 18 | 67.2 | 63.3 | **49.4** | 42.3 | 37.0 | 30.7 |
| 19 | 66.1 | 62.3 | 48.1 | 40.7 | 35.6 | 29.3 |
| 20 | 65.2 | 61.4 | 46.7 | 39.2 | 34.3 | 27.9 |
| 21 | 64.2 | 60.4 | 45.5 | 37.7 | 33.0 | 26.6 |
| 22 | 63.2 | 59.5 | 44.2 | 36.3 | 31.7 | 25.3 |
| 23 | 62.3 | 58.6 | 43.0 | 34.9 | 30.5 | 24.1 |
| 24 | 61.3 | 57.7 | 41.8 | 33.6 | 29.3 | 23.0 |
| 25 | 60.4 | 56.8 | 40.7 | 32.3 | 28.2 | 21.9 |
| 26 | 59.5 | 56.0 | 39.5 | 31.1 | 27.1 | 20.9 |
| 27 | 58.6 | 55.1 | 38.4 | 29.9 | 26.1 | 19.9 |
| 28 | 57.7 | 54.3 | 37.4 | 28.8 | 25.1 | 18.9 |
| 29 | 56.9 | 53.5 | 36.4 | 27.7 | 24.2 | 18.0 |
| 30 | 56.0 | 52.6 | 35.4 | 26.7 | 23.2 | 17.2 |
| 31 | 55.2 | 51.8 | 34.4 | 25.7 | 22.4 | 16.4 |
| 32 | 54.4 | 51.0 | 33.4 | 24.7 | 21.5 | 15.6 |
| 33 | 53.6 | **50.3** | 32.5 | 23.8 | 20.7 | 14.9 |
| 34 | 52.8 | **49.5** | 31.6 | 22.9 | 19.9 | 14.2 |
| 35 | 52.0 | 48.7 | 30.7 | 22.0 | 19.1 | 13.5 |
| 36 | 51.2 | 48.0 | 29.9 | 21.2 | 18.4 | 12.9 |
| 37 | **50.4** | 47.3 | 29.1 | 20.4 | 17.7 | 12.3 |
| 38 | **49.7** | 46.5 | 28.3 | 19.6 | 17.0 | 11.7 |
| 39 | 48.9 | 45.8 | 27.5 | 18.9 | 16.4 | 11.1 |
| 40 | 48.2 | 45.1 | 26.7 | 18.2 | 15.8 | 10.6 |