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

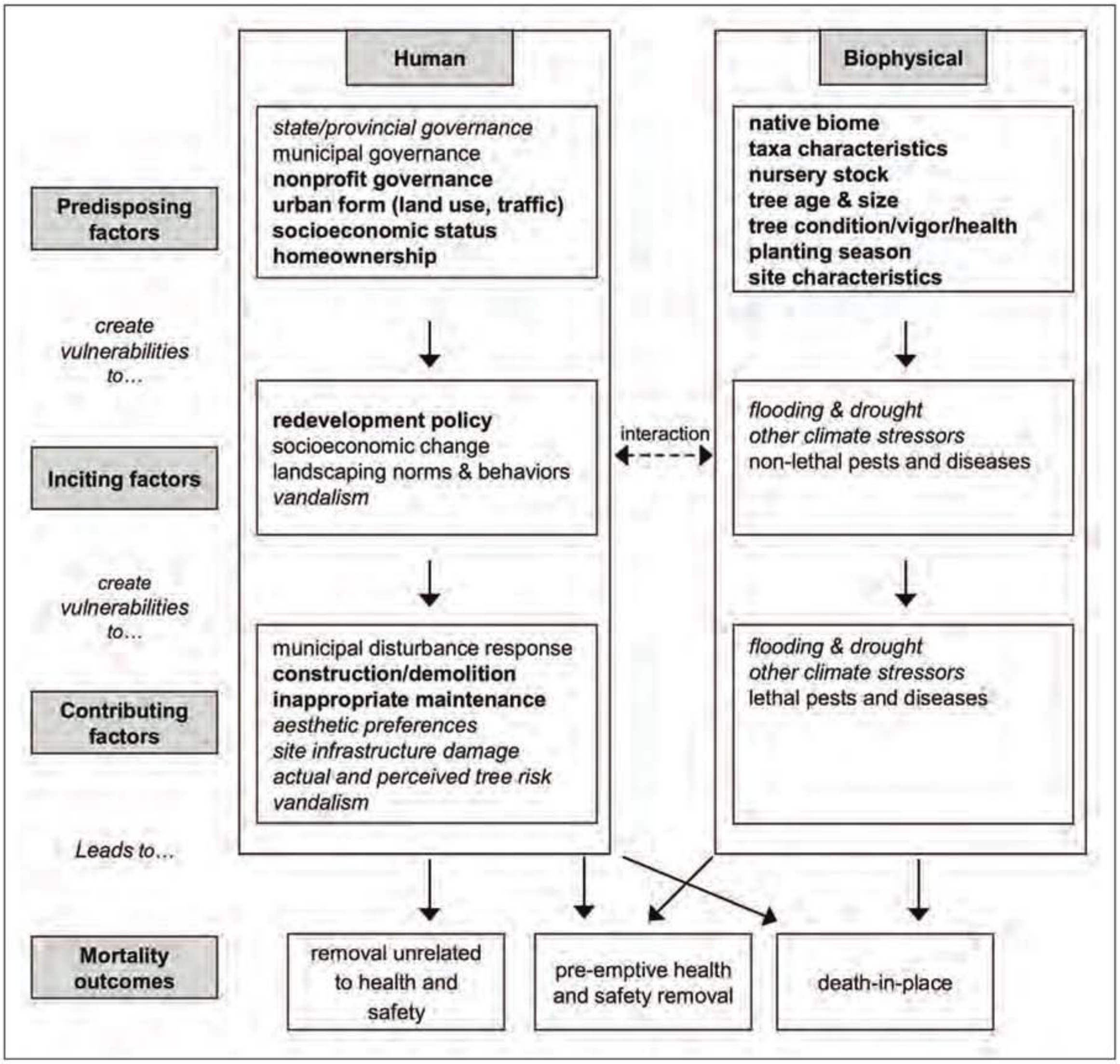

Figure 6. Urban tree mortality framework outlining predisposing, inciting, and contributing factors. The predisposing and inciting factors create vulnerabilities for trees to die or be removed due to the final contributing factors. Solid one-way arrows indicate that predisposing and inciting factors 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),

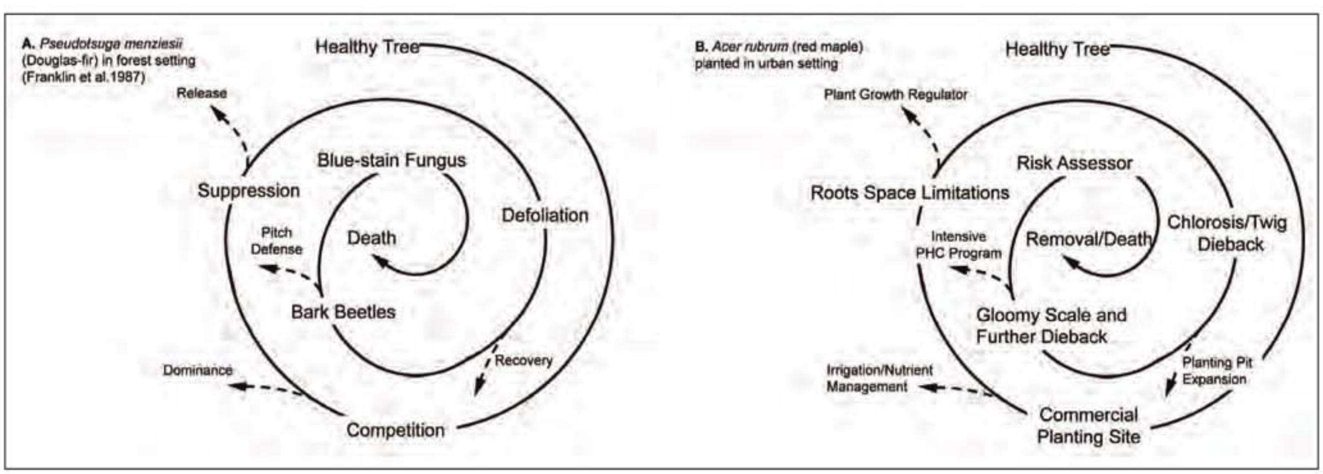

Figure 7. Tree mortality spirals depicting an example tree in a natural forest (adapted from Franklin et al. 1987) and an example planted urban tree.

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, socioeconomic 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 1974 (2300) 1975 (3710) 1976 (3148) 1977 (2463)	1	 6.5 [93.5†] 10.3 [89.7†] 19.7 [80.3†] 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 Milwaukee, redeveloped Milwaukee, not redeveloped Stevens Point Waukesha	Street trees (311) (692) (368) (677)	 4-6 4-6 4-9 4	 10.4-15.8† [51.8] 7.7-11.3† [62] 3.2-7.0† [74.9] 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 1 yr. old 2 yrs. old 3 yrs. old	 1 2 3	 10 [90†] 6.7 [87†] 2.7 [92†]	Includes urban, rural, and agricultural trees.
Sullivan (2004)	San Francisco, CA	Street trees (1987) (1869)	 5 10	 2.9† [86.5] 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 With stewardship Without stewardship	≤ 4	 1.25 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 Total (13,405) 3-6 yrs. cohort (2417) 6-8 yrs. cohort (2417) 8-9 yrs. cohort (5935)	3-9 3-6 6-8 8-9	3.2-9.4† [74.3] 4.0-7.9† [78.2] 3.9-5.1† [73] 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, 0-10 yrs. (793) No construction (391) Construction (402) 11-25 yrs. (895) No construction (686) Construction (219)	10 16	1.8† [83.6] 2.5† [77.9] 1.3† [81.1] 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) park trees (225) yard trees (70)	4-5 3.1 [90.7] 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 Philadelphia, PA Philadelphia, PA	Street trees (568) (150) (94)	5.92 6.25 6.58	0.6 [96.3] 1.6 [90.7] 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 Indianapolis, IN Philadelphia, PA	Street trees (4059)	3-5	7 [79] 7 [80] 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	1		
		1974 (75,653)		2.8	
		1975 (80,493)		2.6	
		1976 (82,374)		3.3	
		1977 (81,581)		1.9	
Dawson and	Urbana, IL	Street trees (1768)	50	1.1	
Nowak (1986)	Syracuse, NY	Street trees (1454)	7	2.4†	Paper also provides mortality rates for species, dbh, curbing, strip width, situation, adjacent land use, utilities, crown, ground disturbance, and condition.
	Syracuse and Rochester, NY	Street trees (1160)	9	2.3†	
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)	2	6.6	Paper also provides mortality for dbh class, condition, and species.
		Transportation (33)		20.2	
		Commercial/		10.6	
		industrial (15)		8.2	
		Urban open (228)		6.0	
		High density		5.9	
		residential (77)		2.2	
		Forest (728)			
		Low-medium density		0	
		residential (136)		0	
		Institutional (4)			
		Barren (7)			
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	> 4		Paper also provides mortality rates for new and established trees based on growing season.
		With stewardship		0.49	
		Without stewardship		1.9	

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 (/) **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 (–) **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 With stewardship Without stewardship	≤ 4 (mixed-aged cohort) > 4 (repeated inventory)	**Human** – Stewardship (+)
Lu et al. (2010)[C]	New York, NY	Street trees Total (13,405) 3-6 yrs. cohort (2417) 6-8 yrs. cohort (5053) 8-9 yrs. cohort (5935)	 3-9 3-6 6-8 8-9	**Biophysical** – Taxa: *Pyrus calleryana* (+) **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* (–) **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* (–) **Human** – Institutional (–), commercial (+)
Jack-Scott et al. (2013)[RI]	New Haven, CT	Community planted trees (1393)	4-16	**Biophysical** – Tree age (–) **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 16	**Biophysical** – Taxa: *Gleditsia triacanthos* (+), *Acer saccharum* (–), trunk diameter (–), planting space width (+), tree condition (+) **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 (+) **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) **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 (−) **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 (−) **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) **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

TREE REMOVAL REPORT

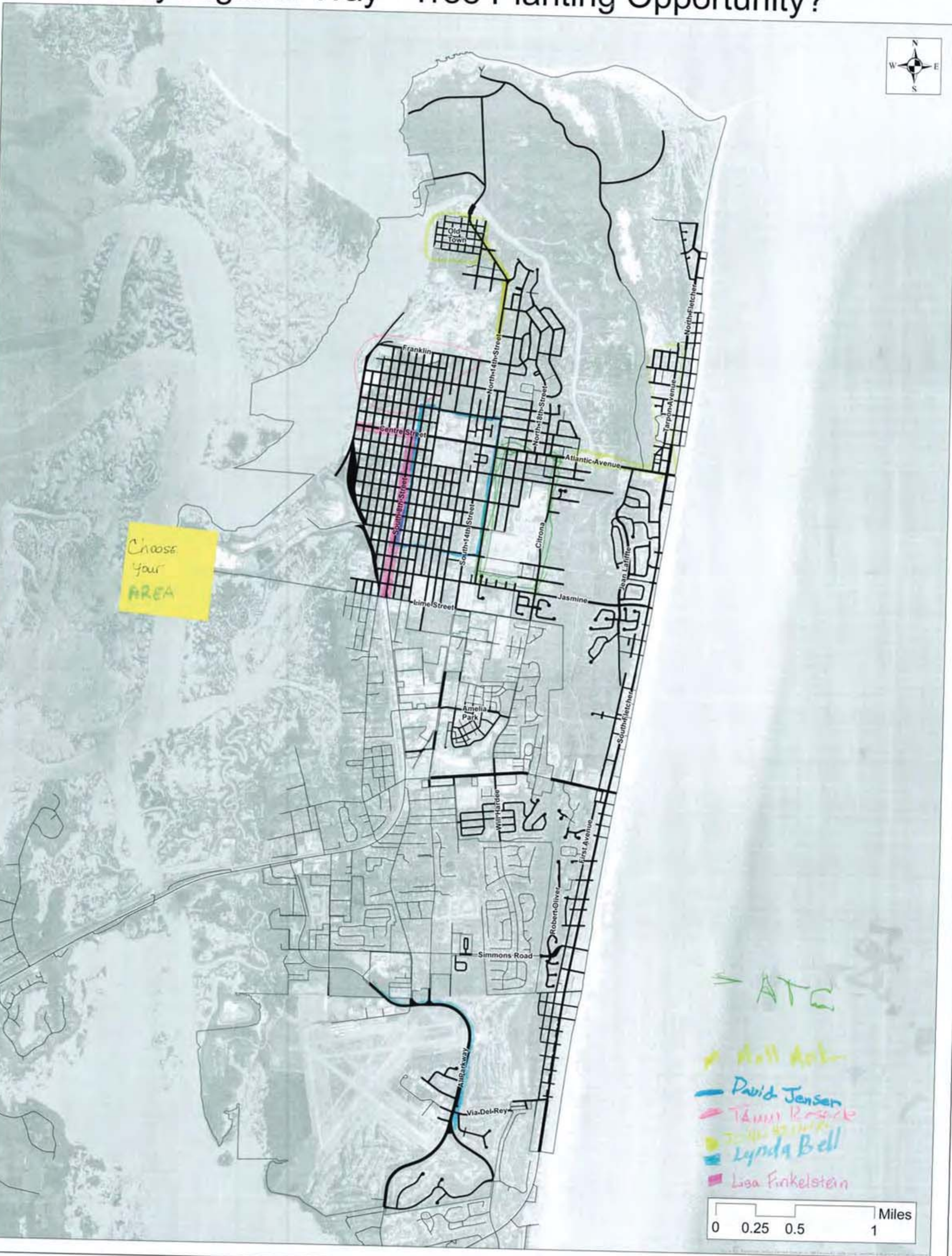
	2014	2015	2016	2017	2018	2019	2020	2021	TOTALS
EXISTING	376	329	315	409	341	225	451	85	2531
NEW HOMES	1724	886	990	2332	2096	820	762	765	10375

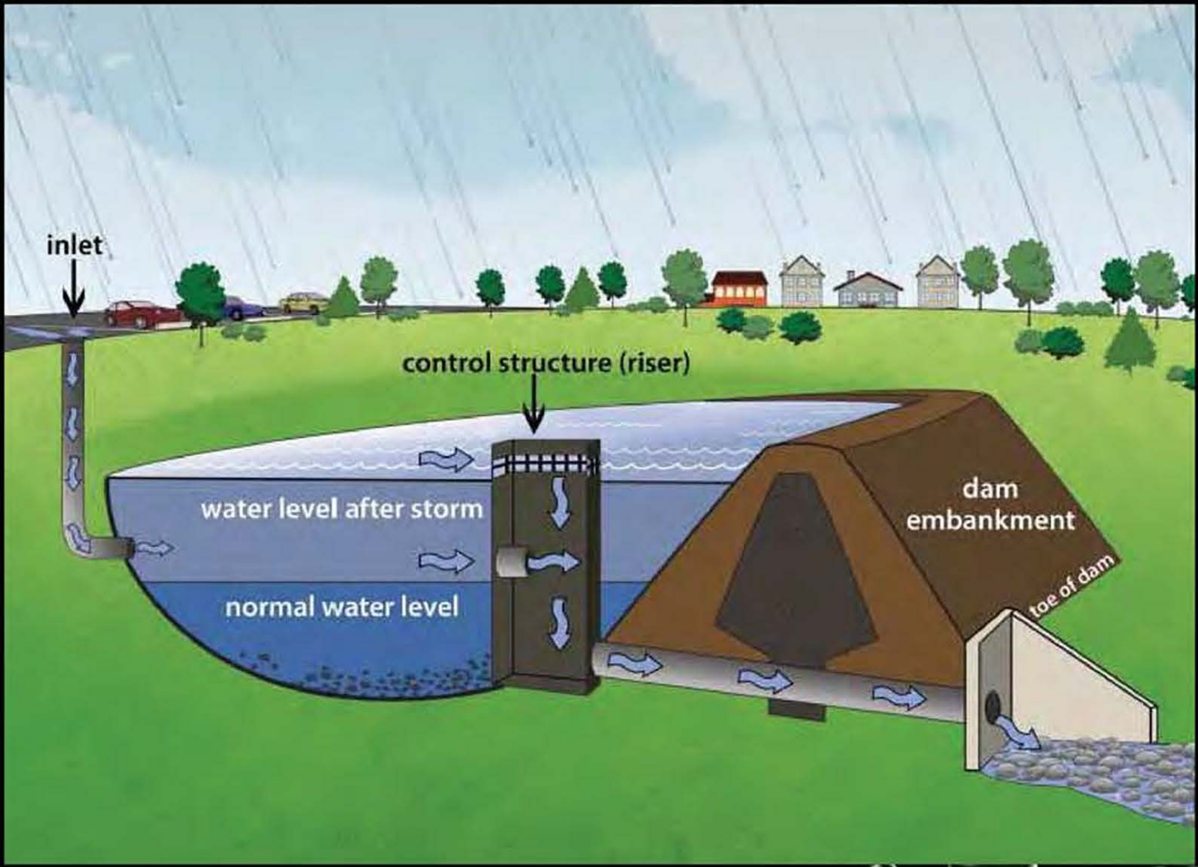
TOTAL REMOVED	12906
Average per year	1613.25

* This data was gathered through reports from created from the IMS system (from 2014 to 2018) and Energov (from 2019 to 2021 YTD)

FUTURE PLANTING PROJECTS – 2021-2022		
Hickory Corridor, ROW (planned)	Along Hickory Street Park and leading into Greenway between Shell Cove and Egans Creek	Planned (150 trees)
Baptist Church, Hickory Street	To be contacted	
Housing Authority, Hickory Street	On-going project	
Amelia Oaks Road, Retention Ponds	To be contacted	
Main Beach Parking lot (planned)	Replacement of concrete island with curbed landscaped beds for trees and cabbage palm and muhly grass	Planned
Sunrise Park, ROW		
Franklin Street, ROW		
Central Park, ROW		
Lighthouse grounds		
Egans Creek Park		
Atlantic Rec Center		
MLK Center		
Peck Center		
Jasmine + Lime Streets	City Maintained Side / Coordinated with adjoining property owners	
S. 10th + S. 11th Streets	Along Date, Elm, Fir and Hickory Streets	
1303 Jasmine Street	In front of Barnabas	
Open Space Opportunities	*Apartment Complexes receiving HUD funding*	
CES 2019 data	*Find where City needs to focus tree replacement efforts*	

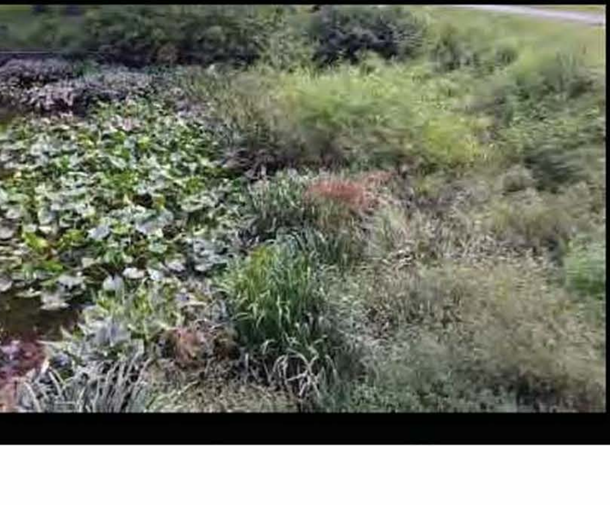
City Right of Way - Tree Planting Opportunity?

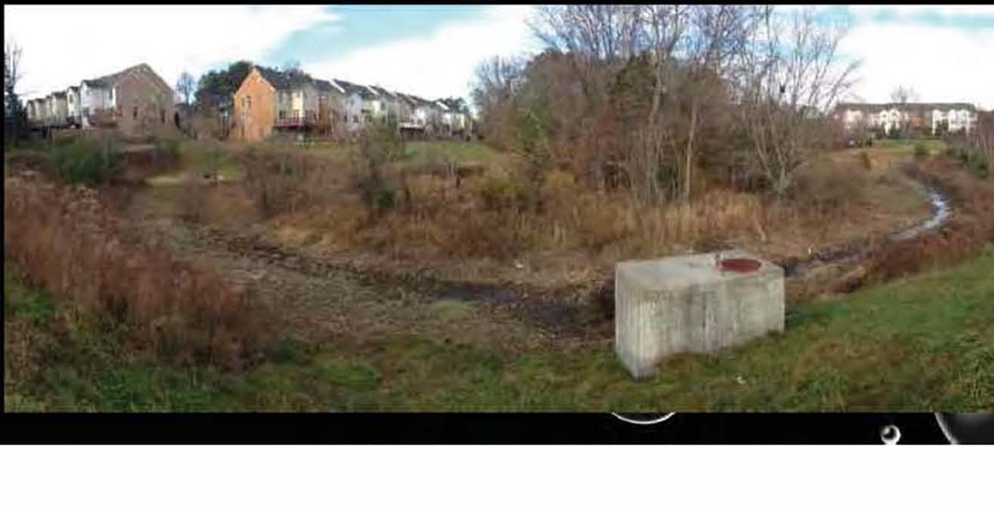



inlet
control structure (riser)
water level after storm
normal water level
dam
embankment
toe of dam

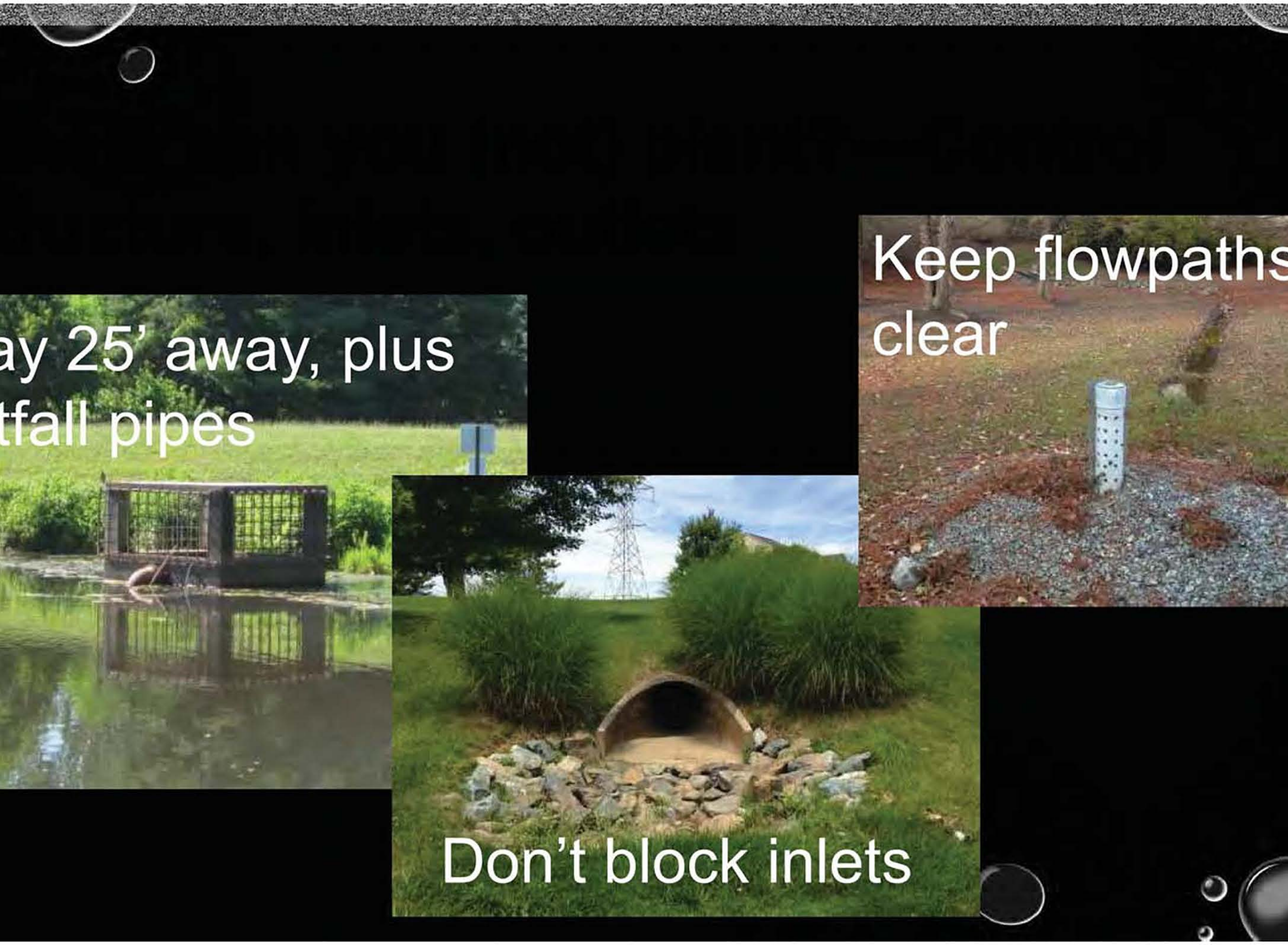
Control
Structure
(Riser)
Dam
Embankment
Flow Paths
Inlet
Toe of Dam

[redacted]

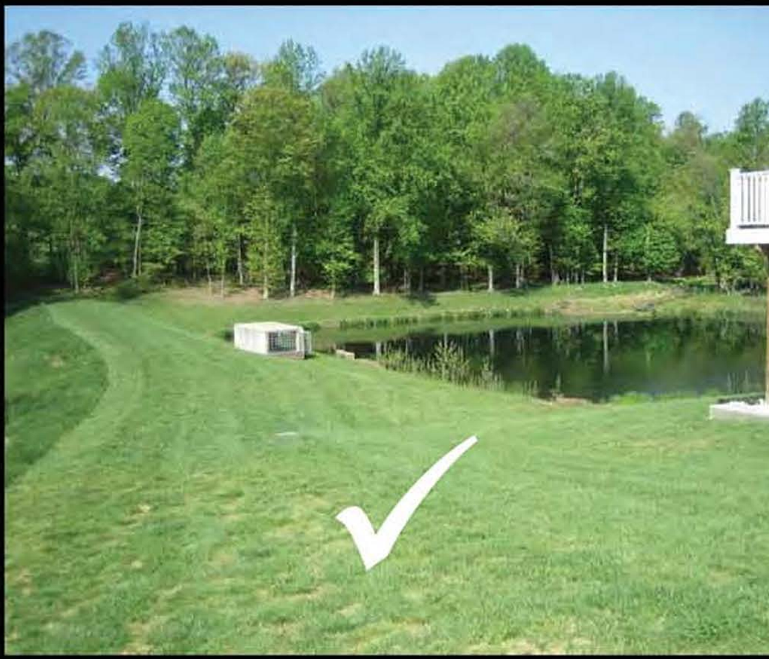





Control Structure (Riser)
Dam Embankment
Flow Paths
Inlet
Toe of Dam



ay 25’ away, plus
tfall pipes
Keep flowpaths
clear
Don’t block inlets


No plants on dams,
or 15' from toe



No planting in sand filters or over pipes

Opportunities to plant—dry bottom