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Street tree survival rates: Meta-analysis of previous studies and application to a field survey in Philadelphia, PA, USA

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ABSTRACT

Low street tree survival rates and the resulting short lifespans are frequently discussed but inadequately quantified in urban forestry literature. This study addresses street tree survival rates with a meta-analysis of previous literature and a case study assessment of street trees in Philadelphia, USA 2–10 years after planting. Reported survivorship rates from 16 previous studies were compiled. Estimated annual survival rates for individual past studies were mostly above 91.0%. To estimate the annual street tree survival rate across multiple studies, a subset of previous studies was pooled for regression analysis of *ln* transformed cumulative survivorship vs. time since planting. Lifespan metrics were estimated using the annual survival rates determined from regression analysis. Based on the meta-analysis, we estimated that street tree annual survival rates ranged from 94.9 to 96.5%, and street tree population half-life ranged from 13 to 20 years. Estimated mean life expectancy ranged from 19 to 28 years, which is considerably longer than the 7- or 13-year street tree average lifespan reported in previous studies. Estimated annual survival rates and lifespan metrics were similar in the Philadelphia case study. Urban forest researchers are encouraged to use demographic concepts and analyses in the study of tree survival and mortality, and to monitor tree survival at repeated time intervals every few years.

Introduction

Street trees are said to have notoriously high mortality rates and low average lifespans. Moll (1989) reported that downtown trees have an average lifespan of 7 years, compared to 32 years for suburban trees. Skiera and Moll (1992) estimated the average lifespan of trees in different land use types using surveys of managers in 20 United States cities. The authors reported an average lifespan of 13 years for downtown street trees, compared with 37 years for residential sites, 60 years for the "best city sites", and 150 years for rural sites. However, the widely cited 7-year (Moll, 1989) and 13-year (Skiera and Moll, 1992) average lifespan figures disagree with the field-based data from other studies (Foster and Blaine, 1978; Richards, 1979; Polanin, 1991; Nowak et al., 2004).

A wide range of street tree lifespans has been reported from field-based studies. Trees along Boston, MA sidewalks were estimated to have an average lifespan of approximately 10 years (Foster and Blaine, 1978), although the procedure to estimate lifespan from Boston mortality data is unclear. Nowak et al. (2004) estimated the average lifespan for urban trees in Baltimore, MD to be 15 years, with 30% of trees living past 15 years. These estimates are based on variable mortality rates for different tree size classes, although Nowak et al. (2004) were not focused exclusively on street trees. Other studies (Richards, 1979; Polanin, 1991) reported the age of surviving trees observed several decades after planting, without including tree deaths in the intervening years. In Jersey City, NJ, Polanin (1991) found that *Acer platanoides* L. had an average "site age" of 48 years, and *Platanus* × *acerifolia* Willd. had an average age of 39 years. Richards (1979) modeled losses for four street tree species in Syracuse, NY to determine average "years of service" per tree as follows: *Gleditsia triacanthos* L. 30 years, *A. platanoides* 55 years, *Acer saccharum* Marsh. 57 years, and *Acer saccharinum* L. 73 years. The terms "site age" and "years of service" indicate ages of observed mature trees. Although different species and planting locations may be expected to have a range of tree lifespans, this enormous range of reported street tree lifespans also speaks to the variety of methods used to assess survival and estimate lifespans. However, methods to quantify tree vital rates and lifespan metrics have been more fully developed in other disciplines; these methods have the potential to advance our understanding of urban tree survival and mortality.

In this study, we estimated annual street tree survival rates by pooling cumulative survivorship data across different time intervals, using (1) a meta-analysis of previous literature and (2) a survey of street trees 2–10 years after planting in Philadelphia, PA, USA.

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The Philadelphia data served as a species and location-specific case study demonstration of the approach used with the meta-analysis. Using the calculated annual survival rates, we also estimated the mean life expectancy (Seber, 1982) and population half-life (Sheil et al., 1995); these terms are measures of lifespan used in demography and population ecology.

Methods

Previous literature data compilation

Published studies and publicly available reports concerning street tree survival or mortality were compiled to develop a comprehensive list of reported street tree mortality rates. Specifically, we searched prominent urban forestry journals (Journal of Arboriculture & Urban Forestry, Urban Forestry & Urban Greening) for any studies concerning street tree survival or mortality. Additional studies were found through the reference lists of the initially identified studies, consultation with colleagues in urban forestry, and internet searches for street tree mortality or survival.

Sixteen studies were identified (Table 1). Most studies were found in scientific journals or proceedings (Urban, 1989), but two unpublished program reports (Sullivan, 2004; Gates and Lubar, 2007) and one university bulletin (Sydnor et al., 1999) that are publicly available were also included. The compiled studies all concern cities in temperate regions. Because of the small number of available studies, all studies were considered eligible for meta-analysis, without regard for differences in climate, level of urbanization, management regime, and other factors that might affect tree survival. These 16 studies varied greatly in their methods, especially the time interval between tree planting and survival assessment. Most studies exclusively measured trees described as street, sidewalk, or streetside. One study included replacement trees in the reported survival rates (Sklar and Ames, 1985). One study of urban tree mortality (Nowak et al., 2004) was not included in data compilation because results did not differentiate street tree mortality rates.

Philadelphia street tree field survey

To assess street tree survival in Philadelphia, we surveyed trees planted by the Philadelphia Green program of the Pennsylvania Horticultural Society in the neighborhoods of North Philadelphia (zip codes 19122, 19125, 19133). The study area is located immediately north of the central business district, and is characterized by high rates of vacant land and low income residents (U.S. Census Bureau, 2000). We surveyed all *Acer campestre* L. street trees planted in the years 1995–2003 in the specified zip codes, for a total sample size of 151 trees. The geographic area and species were selected because they offered the best sample size for recent plantings in the Philadelphia Green database. Field work for this study was conducted June–September 2005. Trees were recorded as alive or dead, with the dead category including both standing dead and removed trees.

Data analysis

Data from both the previous studies and the Philadelphia field survey were analyzed using equations from demography and population ecology for annual mortality, annual survival, cumulative survivorship, mean life expectancy, and population half-life. Annual mortality is defined by $m_{\text{annual}} = 1 - (N_t/N_0)^{1/t}$, where N_0 and N_t are population numbers at the beginning and end of time interval t (after Sheil et al., 1995, Eq. (6)). In the context of street tree survival after planting, N_0 is the number of trees planted at $t = 0$, and N_t is the number of trees alive at the end of time interval t. The fraction N_t/N_0 is the cumulative survivorship to time t, conventionally written l_t. The relationship between annual mortality and annual survival is $l_{\text{annual}} = 1 - m_{\text{annual}}$, which leads to $l_{\text{annual}} = (l_t)^{1/t}$, or stated equivalently, $l_t = (l_{annual})^t$. These relationships assume constant probability of mortality over time. The assumption of constant mortality corresponds to a Type II survivorship curve (Harcombe, 1987), in which *ln* transformed survivorship l_t decreases linearly over time, and l_t itself decreased exponentially over time. The abbreviation *ln* denotes the natural logarithm (base *e*).

Mean life expectancy is calculated from annual survival by $e_0 = -1/ln(l_{\text{annual}})$, where e_0 is the mean life expectancy from time of planting, or $t = 0$ (after Seber, 1982, Eq. (1.3)). Plant ecologists sometimes report the population half-life, or the time at which cumulative survivorship is 50% (i.e., when half the population has died). The population half-life is defined by $t_{0.5} = ln(0.5)/ln(l_{\text{annual}})$ (after Sheil et al., 1995, Eq. (10)). These relationships also assume constant probability of mortality over time.

With the above explanation of terms, the methods can be stated succinctly. The approach for both the meta-analysis and the Philadelphia field survey was to pool l_t data from different time intervals in order to estimate l_{annual}, and from there, to also estimate e_0 and $t_{0.5}$.

Meta-analysis of previous literature

To compare the cumulative survivorship rates reported in previous studies, we estimated the annual survival rates separately for each study using $l_{\text{annual}} = (l_t)^{1/t}$. Annual survival rates were only estimated for studies that reported l_t from the time of planting. Conservative figures were taken when a range of survival or time period was reported (e.g., 60–70% survival was reduced to 60%, 5–10 years was reduced to 5 years). This conservative approach takes the minimum possible survival from reported data. We summarized the estimated annual survival rates from individual studies by reporting the range and quartiles. We excluded Sklar and Ames (1985) from these summary statistics, because replacement trees were included in reported survivorship.

To combine cumulative survivorship data from many previous studies to estimate typical street tree annual survival, we used linear regression analysis of *ln* transformed cumulative survivorship l_t vs. time period since planting t. This relationship also represents a Type II survivorship curve with constant mortality (Harcombe, 1987). Although other survivorship curve shapes may apply to urban trees, only Type II was considered here for simplicity of estimating mean life expectancy and population half-life.

Of the 16 complied studies, those which reported cumulative survival rates at a specified the time period since planting (l_t) were included in meta-analysis. Survival rates of existing street trees (i.e., the time interval does not begin at planting) are included in data compilation but excluded from meta-analysis. We excluded Sklar and Ames (1985) from regression analysis because replacement trees were part of the reported survival rates. Eleven studies were therefore used in regression analysis (Table 1).

When the reported cumulative survivorship was zero (Sydnor et al., 1999), *ln* transformation was estimated as $ln(0.1) = -2.3$. The *y*-intercept was constrained to 100% survival rate at the time of planting [$ln(100) = 4.60517$]. All data points were used (i.e., multiple values from the same study were permitted). Conservative figures (i.e., minimum survival) were again taken when a range of survival or time period was reported; we also tried maximum survival for comparison. Regression analysis was conducted with and without weighting by sample size N_0. Weighting was done because studies with larger sample sizes have more information to contribute; weighting is often used to compensate for disparate sample sizes in meta-analysis in other contexts (Schmidt et al., 2009). In weighted regression models, Gerhold et al. (1994) was excluded because

Table 1

Summary of street tree survival rates from available literature. Time period begins with year(s) planted or initially surveyed. Survival rates marked "‡" were not included in regression analysis or summary statistics. Survival rates marked "E" measured survival of already established trees; for all other studies, "survival rate" is survivorship after planting l_t, as defined in the text. When studies reported a range of survivorship and time periods, the minimum estimated annual survival rate was calculated.

Location	Study groups (sample size N_0)		Survival rate (%)	Time period t (yrs)	Estimated annual survival l_{annual} (%)	Source
Oakland, CA	All species					Sklar and Ames (1985)
	W/community participation	(1,500)	~60–70‡	~5	90.3	
	W/out community participation	(2,000)	~0.5‡	~5–10	34.7	
Oakland, CA	All species	(480)	66	2	81.2	Nowak et al. (1990)
San Francisco, CA	All species	(1,987)	86.4	5	97.1	Sullivan (2004)
		(1,869)	67.9	10	96.2	
IA small towns	All species	(214)	87.0	4–5	96.6	Thompson et al. (2004)
Urbana, IL	All species	(1,768)	4.4$^{\ddagger\,\mathrm{E}}$	50	n/a	Dawson and Khawaja (1985)
Boston, MA						Foster and Blaine (1978)
Beacon Hill	All species	(215)	39$^{\ddagger\,\mathrm{E}}$	10	n/a	
Beacon St.	*Tilia* spp.	(350)	23	66	97.8	
Boylston St.	All species	(136)	74	2–4	86.0	
Syracuse, NY	*Acer platanoides* L.	(unk.)	75.0$^{\ddagger\,\mathrm{E}}$	27	n/a	Richards (1979)
	A. saccharinum L.		75.0$^{\ddagger\,\mathrm{E}}$		n/a	
	A. saccharum Marsh.		47.0$^{\ddagger\,\mathrm{E}}$		n/a	
	Gleditsia triacanthos L.		30.0$^{\ddagger\,\mathrm{E}}$		n/a	
OH						Sydnor et al. (1999)[a]
Cleveland	*Liquidambar styraciflua* L.	(68)	64.7	45	99.0	
Cleveland	*Acer pseudoplatanus* L.	(65)	29.2	42	97.1	
Cleve. Area	*Prunus serrulata* Lindl.	(50)	0	41	–	
Cleve. Area	*Betula pendula* Roth	(53)	0	40	–	
Cleveland	*A. rubrum* L.	(57)	87.7	39	99.7	
Cleve. Area	*Crataegus phaenopyrum* Borkh.	(50)	2.0	38	90.2	
Columbus	*A. platanoides*	(84)	46.4	38	98.0	
Toledo	*A. platanoides*	(80)	56.3	34	98.3	
Toledo	*A. platanoides*	(71)	15.5	32	94.3	
Cleve. Area	*G. triacanthos*	(76)	92.1	30	99.7	
Philadelphia, PA	All species	(50)	84.0	2	91.7	Gates and Lubar (2007)
		(571)	93.5	1.5	95.6	
		(705)	93.3	1	93.3	
PA & MD small towns	*Malus* spp.	(unk.)	94–100	3	98.0	Gerhold et al. (1994)
WI						Miller and Miller (1991)
Milwaukee	All species	(1,003)	58.8	4–6	87.6	
Waukesha		(677)	76.5		93.5	
Stevens Point		(368)	74.9	4–9	93.0	
Milwaukee, WI	All species			10		Hauer et al. (1994)
	Damaged by constr.	(432)	77.3		97.5	
	Undamaged	(413)	81.4		98.0	
Northeastern US cities		(1,333)	93.3‡	(standing dead trees)	n/a	Urban (1989)
Brussels, Belgium	All species, newly planted	(2,300)	93.5	1	93.5	Impens and Delcarte (1979)
		(3,710)	89.7	1	89.7	
		(3,148)	80.3	1	80.3	
		(2,463)	91.3	1	91.3	
	All species, existing	(75,653)	97.2$^{\ddagger\,\mathrm{E}}$	1	n/a	
		(80,493)	97.4$^{\ddagger\,\mathrm{E}}$	1	n/a	
		(82,374)	96.8$^{\ddagger\,\mathrm{E}}$	1	n/a	
		(81,581)	98.1$^{\ddagger\,\mathrm{E}}$	1	n/a	
Beijing, China	All species	(750)	25.1	0.25	0.4	Yang and McBride (2003)
North England cities	All species and towns	(unk.)	90.3‡	(unk.)[b]	n/a	Gilbertson and Bradshaw (1985)

[a] For Sydnor et al. (1999), only planting cohorts with $\geq$50 trees were included.

[b] For Gilbertson and Bradshaw (1985), time period was reported as "newly planted", and survival rate reflects percent of live trees among those encountered.

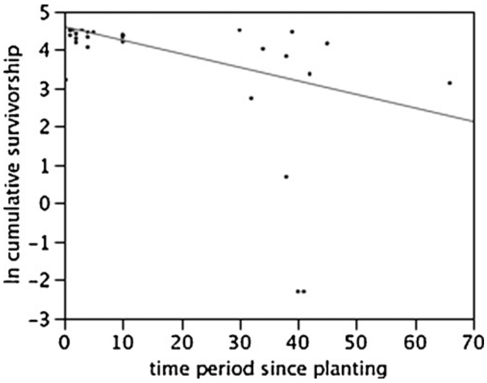

Fig. 1. Meta-analysis of *ln* transformed street tree cumulative survivorship ($ln\, l_t$) vs. time period since planting (t, years), weighted by sample size. See Table 1 for a list of the studies included and Table 2 for regression model outputs.

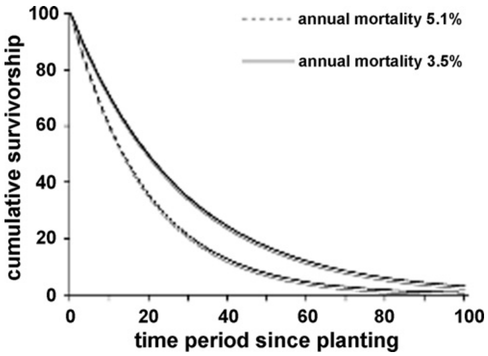

Fig. 2. Survivorship curves when annual mortality rate is constant at 5.1% or 3.5%, as estimated from the meta-analysis. These curves depict exponential decay of survivorship (l_t) over time (t, years), without *ln* transformation (Table 2).

sample size was not reported, resulting in 10 studies for regression analysis. The statistical analysis software JMP 8 (SAS Institute, 2009) was used for regression analysis.

Analysis of A. campestre in Philadelphia

Linear regression analysis was used to analyze *ln* transformed cumulative survivorship l_t of *A. campestre* vs. time period since planting t. As with the meta-analysis, the y-intercept was constrained to 100% survival at the time of planting, and regression analysis was conducted with and without weighting by sample size N_0 (i.e., different numbers of trees were planted during different years).

Results

Meta-analysis of previous literature

Street tree survival rates varied greatly among the previous studies (Table 1), with estimated annual survival ranging from 0.4% to 99.7%. The median estimated annual survival rate is 95.0%, and the 25th and 75th percentiles are 91.0% and 97.8%, respectively. Thus, the estimated annual survival rates for 75% of the studies were above 91.0%. Only two studies had estimated annual survival rates below 80% (Sklar and Ames, 1985; Yang and McBride, 2003), and one of these (Sklar and Ames, 1985) was already excluded from summary statistics and meta-analysis.

For the 10 studies included in regression analysis using weighting by sample size N_0, *ln* transformed cumulative survivorship l_t is weakly correlated ($R^2 = 0.38$, $p = 0.0003$) with time period since planting t (Fig. 1 and Table 2). The equivalent exponential decay model is $l_t = 100(0.965)^t$ (Table 2), thus estimated annual survival rate is 96.5% (Fig. 2). Based on this annual survival rate, mean life expectancy is estimated to be 28 years, with a population half-life of 20 years. For the 11 studies included in regression analysis without weighting, $ln\, l_t$ is again weakly correlated ($R^2 = 0.43$, $p < 0.0001$) with t (Table 2). In this case, estimated annual survival rate is 94.9% (Fig. 2), with a mean life expectancy of 19 years, and a population half-life of 13 years.

The estimated annual survival rates reported above assumed minimum possible survival when studies reported a range of survivorship and time periods. When we ran the regression analysis with the maximum survival assumption, estimated annual survival did not change substantially within the number of digits reported. With the maximum survival assumption, estimated annual survival rates increased slightly, but within the rounding error; annual survival rates were again 96.5% for the weighted approach and 94.9% for the approach without weighting.

Because Sklar and Ames (1985) and Yang and McBride (2003) have unusually low survival, these data points may be considered outliers. In the regression analysis of previous data, Sklar and Ames (1985) were already excluded for other reasons. Removing Yang and McBride (2003) from the regression analysis did not substantially change the estimates of annual survival within the reported digits. With this study removed, estimated annual survival rates increased slightly, but within the rounding error; annual survival rates were again 96.5% for the weighted approach and 94.9% for the approach without weighting.

Analysis of A. campestre in Philadelphia

There was a moderately strong correlation ($R^2 = 0.76$, $p = 0.0023$) between $ln\, l_t$ of *A. campestre* in North Philadelphia with t when weighted by sample size (Tables 2 and 3). In this case, estimated annual survival rate is 95.5%, mean life expectancy 22 years, and population half-life is 15 years. Without weighting, the relationship between $ln\, l_t$ and t is borderline significant and weakly correlated ($R^2 = 0.36$, $p = 0.0789$). For this analysis, estimated annual survival

Table 2
Linear regression models for $ln(l_t)$ vs. t for meta-analysis of previous literature, and for Philadelphia field survey. The equivalent exponential decay models are in the form $l_t = 100(l_{annual})^t$. The sample size N_0, mean life expectancy e_0, and population half-life $t_{0.5}$ are defined in the text.

	Regression model	Exponential decay model	Regression model outputs		Lifespan metrics	
			p	R^2	e_0	$t_{0.5}$
Meta-analysis of previous literature						
Weighted by N_0	$ln(l_t) = 4.60517 - (0.0352911)t$	$l_t = 100(0.965)^t$	0.0003	0.3768	28	20
Not weighted by N_0	$ln(l_t) = 4.60517 - (0.05221)t$	$l_t = 100(0.949)^t$	<0.0001	0.4320	19	13
Philadelphia field survey						
Weighted by N_0	$ln(l_t) = 4.60517 - (0.0456613)t$	$l_t = 100(0.955)^t$	0.0023	0.7569	22	15
Not weighted by N_0	$ln(l_t) = 4.60517 - (0.0348329)t$	$l_t = 100(0.966)^t$	0.0798	0.3645	29	20

Table 3
Cumulative survivorship of *A. campestre* in North Philadelphia planted 2–10 years ago. Each row represents a different planting cohort.

Time period t (year planted)	# Planted (sample size N_0)	# Alive 2005	Survivorship l_t (%)
10 (1995)	2	2	100.0
9 (1996)	30	19	63.3
7 (1998)	17	10	58.8
6 (1999)	10	10	100.0
5 (2000)	22	21	95.5
4 (2001)	45	35	77.8
3 (2002)	2	1	50.0
2 (2003)	23	23	100.0
Total	151	119	

rate is 96.6%, mean life expectancy 29 years, and population half-life is 20 years.

Discussion

The goal of this research was to advance our understanding of urban forest mortality and survival by estimating annual street tree survival rates and lifespan metrics from the available data. Meta-analysis of published street tree survivorship rates indicated that the annual survival rate was 94.9–96.5%, with a corresponding annual mortality rate of 3.5–5.1% (Fig. 2 and Table 2). The annual survival rates determined from regression meta-analysis are consistent with the annual survival rates estimated separately for individual past studies (median 95.0%, most above 91.0%).

The street tree mean life expectancy estimated from meta-analysis (19–28 years) is higher than the 7- or 13-year street tree average lifespans suggested by Moll (1989) and Skiera and Moll (1992). However, mean life expectancy has an established definition in demography (Seber, 1982), while average lifespan has not been clearly defined. If we treat the 7-year average lifespan as a mean life expectancy, the estimated annual survival rate would be 86.7%, considerably lower than the annual survival rates calculated from meta-analysis and estimated from most of the individual studies (Tables 1 and 2).

However, mean life expectancy may not always be the most useful metric to understand urban forest survival trends. With very low (<1%) annual mortality rates, estimated mean life expectancy would reach hundreds or thousands of years, because of the asymptotic relationship between annual mortality and mean life expectancy (Nowak et al., 2004) inherent in the definition of e_0 (Seber, 1982). For practical applications in predicting tree loss and replacement needs, the population half-life $t_{0.5}$ (Sheil et al., 1995) may be more useful. In our meta-analysis, the population half-life was estimated to be 13–20 years (Table 2). Using an equation similar to the population half-life equation, one can also estimate the time at which 75% of the population remains alive by $t_{0.75} = ln(0.75)/ln(l_{\text{annual}})$, and projections for other future survivorship rates are similar. Urban forest researchers may also find the population half-life a useful concept to project survivorship rates for cost-benefit analyses, which are sensitive to assumed mortality rates (Hildebrandt and Sarkovich, 1998; McPherson et al., 1998; McPherson and Simpson, 2001; McPherson and Simpson, 2003).

The estimated annual street tree survival rate of 94.9–96.5% from meta-analysis must still be considered a first-round assessment. Because the studies included in our meta-analysis often lacked detail about sampling procedures, we did not attempt to estimate sampling or measurement error. Several studies reported ranges of survivorship values and time periods since planting, and although our results did not substantially change with different approaches to dealing with those studies, this issue is representative of a lack of precision and detail in some past urban tree mortality studies. Additional street tree survival data from urban planting programs may remain unpublished in scientific journals; community organizations should be encouraged to make their data public to contribute to our collective understanding of urban tree survival.

Furthermore, for studies included in the meta-analysis, when survivorship is reported many years or decades after planting, without tree monitoring during the intervening years, we have no way to ascertain when the mortality events occurred. In survival analysis, this situation is referred to as left censoring: the lifespans of individual trees that died during the observation interval are unknown. Our approach does not attempt to compensate for censoring. For simplicity in our analysis, annual mortality was assumed to be constant. This corresponds to a Type II survivorship curve, in which the *ln* transformed survivorship decreases linearly over time (Harcombe, 1987). However, urban forest researchers have suggested that the first several years after planting, referred to as the establishment period, have the highest annual mortality rates (Richards, 1979; Miller and Miller, 1991). A Type III survivorship curve, which depicts decreasing probability of mortality over time (Harcombe, 1987), corresponds to the scenario of high mortality rates for young individuals. It has been suggested that wildland trees have a U-shaped mortality curve with regard to size, in which annual mortality is high for small understory trees, low and steady for mature overstory trees, and high again for very large trees reaching their maximum life expectancy (Harcombe, 1987; Lorimer et al., 2001). Urban trees may follow a similar pattern, but we need more mortality data to explore the suitability of different survivorship curve shapes. Although our analysis is admittedly limited by our assumption of constant mortality, and by the long time periods between observations in many studies, we assert that the results presented here represent considerable progress in applying concepts and methods from other disciplines to available urban tree survivorship data.

The Philadelphia field survey demonstrated a technique for pooling survivorship data from a specific street tree planting program in order to estimate context-specific annual survival rates. This case study application of the methods used in meta-analysis yielded similar annual mortality rates and lifespan metrics (Table 2). Other urban forestry programs may employ this method to estimate their annual tree survival rates based on past planting records. However, other approaches to assessing urban tree mortality would avoid the limitations posed by left censored data over large time intervals. Surveying a cohort of urban trees from the time of planting, and continuing with annual mortality surveys, would facilitate the construction of an age-based survivorship curve. Wildland forest populations are often treated with stage-based survivorship curves, with tree diameter class substituting for age class (Harcombe, 1987). This approach could be applied when mortality rates are assessed for existing urban trees of varying size classes (e.g., Nowak et al., 2004).

To assess how annual urban tree mortality varies in the years after planting, future studies should consider using life table projections (Harcombe, 1987) and longitudinal analysis (Woodall et al., 2005). Researchers should partner with local urban forestry programs to monitor tree survival at regular intervals every few years, ideally annually or bi-annually. Such studies would enhance our understanding of urban tree mortality rates, allowing us to construct survivorship curves that improve predicted tree replacement needs and cost-benefit analyses.

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