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# The balance of planting and mortality in a street tree population

**Lara A. Roman · John J. Battles · Joe R. McBride**



**Abstract** Street trees have aesthetic, environmental, human health, and economic benefits in urban ecosystems. Street tree populations are constructed by cycles of planting, growth, death, removal and replacement. The goals of this study were to understand how tree mortality and planting rates affect net population growth, evaluate the shape of the mortality curve, and assess selected risk factors for survival. We monitored a street tree population in West Oakland, CA for 5 years after an initial inventory (2006). We adapted the classic demographic balancing equation to quantify annual inputs and outputs to the system, tracking pools of live and standing dead trees. There was a 17.2 % net increase in live tree counts during the study period (995 in 2006, 1166 in 2011), with population growth observed each year. Of the live trees in 2006, 822 survived to 2011, for an annual mortality rate of 3.7 %. However, population growth was constrained by high mortality of young/small trees. Annual mortality was highest for small trees, and lower for mid-size and large trees; this represents a Type III mortality curve. We used multivariate logistic regression to evaluate the relationship between 2011 survival outcomes and inventory data from 2006. In the final model, significant associations were found for size class, foliage condition, planting location, and a multiplicative interaction term for size and foliage condition. Street tree populations are complex cultivated systems whose dynamics can be understood by a combination of longitudinal data and demographic analysis. Urban forest monitoring is important to understand the impact of tree planting programs.

**Keywords** Demography · Monitoring · Mortality curve · Oakland · Survivorship · Urban forest

## Introduction

Street trees are essential to the green infrastructure of cities. These trees—located in sidewalk cut-outs, street-side planting strips, and medians—have aesthetic, environmental,

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public health, and economic benefits (Dwyer et al. 1992; McPherson and Simpson 2002; Nowak and Dwyer 2007). Many great streets and boulevards are characterized by their trees (Lawrence 1988; Jacobs 1995). Street trees improve air quality, reduce stormwater runoff, sequester carbon dioxide, shade buildings to reduce energy use (McPherson and Simpson 2002; McPherson 2003; McPherson et al. 2005), increase property values (Laverne and Winson-Geideman 2003; Donovan and Butry 2010, 2011), and promote consumer behavior in business districts (Wolf 2003, 2004). Urban areas with more street trees have been associated with lower prevalence of childhood asthma (Lovasi et al. 2008). Street trees also contribute to urban design aesthetics and walkable, livable neighborhoods (Appleyard 1981; Southworth 2003, 2005; Tilt et al. 2007; Merse et al. 2008). The planting and maintenance of street trees are central components of urban forestry programs around the world. To maximize the value of urban tree planting initiatives, these trees must survive to maturity, when canopy cover and associated benefits are greatest.

Street tree populations are constructed by human-driven cycles of planting, growth, death, removal, and replacement. To increase the overall number of street trees in a given city or neighborhood, the number of newly planted trees must exceed losses from death and removal. Tree size and age class distribution are important to street tree population stability, with an adequate proportion of recently planted young, small trees needed to offset early mortality (Richards 1983; McPherson and Rowntree 1989; Maco and McPherson 2002). Richards (1979) suggested that young street tree death—as opposed to older tree mortality—was the primary determinant of the replacement rate needed to maintain the street tree community in Syracuse, NY. Projecting future changes and replacement planting needs (Richards 1979; Bartsch et al. 1985; Brack 2006) in urban tree populations requires information on tree mortality and planting rates (Nowak et al. 2004).

Demographic concepts, such as survivorship and mortality curves, are useful to analyze urban tree mortality rates (Roman and Scatena 2011). Size-based mortality curves, which illustrate how death rates vary by size class, are widely discussed in forest ecology (Buchman 1983, 1985; Harcombe and Marks 1983; Buchman and Lentz 1984; Harcombe 1987; Monserud and Sterba 1999; Lorimer et al. 2001; Umeki 2002; Coomes and Allen 2007; Metcalf et al. 2009; Lines et al. 2010). Trees in wildland (i.e., non-urban) forests generally follow U-shaped mortality curves with respect to trunk diameter size class (Harcombe 1987; Lines et al. 2010), in which annual mortality is relatively high for small understory trees, low and steady for mature overstory trees, and rises again for very large trees. Street trees may follow a similar U-shaped mortality curve, albeit with different causal mechanisms. The first several years after planting, referred to as the establishment period, may have the highest annual mortality rates (Richards 1979; Miller and Miller 1991). Street tree death rates may stabilize for mid-size trees, then rise again in the larger size classes with senescence-related death (Richards 1979), and removal of large trees that are hazardous to infrastructure or property (Harris et al. 2004; Smiley et al. 2007). For example, size-based mortality rate data from street trees in Syracuse, NY (Nowak 1986) followed a U-shaped mortality curve, as did mortality rates for trees across the urban landscape in Baltimore, MD (Nowak et al. 2004). Another mortality curve shape observed in wildland forests is the Type III curve, in which mortality rates are highest for small trees, and low for mature and very large trees (Harcombe 1987; Lorimer et al. 2001). Identifying the shape of the street tree mortality curve would be useful for urban forest management by improving our understanding of tree death and removal rates, and subsequent replacement needs. Accurate mortality curves would also be useful in cost-benefit analyses of urban forest ecosystem services, which are sensitive to assumed mortality rates (Hildebrandt and Sarkovich 1998; McPherson et al. 1998, 2008; McPherson and Simpson 2003; Morani et al. 2011).

Previous studies of urban tree mortality have identified numerous causes of tree death and removal, including biophysical and social factors. Urban tree mortality has been associated with species, size, and health condition of the tree, as well as planting location and land use at the site (Nowak et al. 1990, 2004; Lu et al. 2010; Lawrence et al. 2011). Socioeconomic status of the neighborhood, vandalism, and community involvement have also been connected to mortality (Sklar and Ames 1985; Nowak et al. 1990; Pauleit et al. 2002; Boyce 2010; Lawrence et al. 2011). Other factors contributing to urban tree mortality include compacted and contaminated soils (Grabosky and Bassuk 1995; Craul 1999; Scharenbroch et al. 2005), water stress (Whitlow et al. 1992; Nielsen et al. 2007), construction damage (Hauer et al. 1994), nursery production and transplanting technique (Ferrini et al. 2000), extreme weather events (Hauer et al. 1993; Duryea et al. 1996, 2007; Staudhammar et al. 2011), and invasive pests and pathogens (Dreistadt et al. 1990; Poland and McCullough 2006; Lacan and McBride 2008). However, previous urban tree mortality studies commonly investigated risk factors for tree death with univariate analysis (Nowak et al. 1990, 2004; Lu et al. 2010), assessing each factor individually without accounting for confounding or interactions among factors. To understand the causes of tree death in complex urban environments, researchers should assess the strength of individual factors in multivariate models (e.g., Lawrence et al. 2011; Staudhammar et al. 2011), which are widely applied in mortality research in forest ecology (e.g., Das et al. 2007; Lines et al. 2010) and public health (Hosmer and Lemeshow 2000; Jewell 2004).

In this study, we used 5 years of street tree monitoring data from the neighborhood of West Oakland, CA to investigate mortality rates and risk factors. Our research objectives were to 1) determine how the street tree population size changed over the study period, in relation to annual planting and mortality rates; 2) assess the shape of the street tree mortality curve; and 3) analyze the association between selected risk factors and survival with multivariate logistic regression.

## Methods

### Site description

This study took place in Oakland, CA, a Mediterranean climate city whose tree cover has increased with human settlements due to current and historic community-driven tree planting initiatives (Cole 1979; Nowak 1993). The research site is located in the West Oakland neighborhood and encompasses approximately 12 by 12 city blocks (bounded by 35$^{th}$ St., Martin Luther King, Jr. Way, West Grand Ave., and Peralta St.). The USDA Forest Service and Urban Releaf, a local non-profit organization, completed a street tree census in 2006 as a baseline to model hydrologic effects of increased street tree population and canopy cover (USDA Forest Service 2006; Xiao and McPherson 2011).

West Oakland is a predominantly African-American and low-income community (Costa et al. 2002; Gonzales et al. 2011). The neighborhood has a concentration of pollution sources from highways and industry, including the Port of Oakland and trucking businesses (Costa et al. 2002; Fisher et al. 2006; Gonzales et al. 2011), and high rates of childhood asthma and lead poisoning (Costa et al. 2002). In response to these environmental justice concerns, West Oakland is the focus of street tree planting efforts by Urban Releaf and the City of Oakland. The research site has a residential, commercial, industrial, and institutional land uses, often mixed within a city block.

## Field data collection

The initial 2006 street tree inventory followed i-Tree Streets (formerly STRATUM) protocols (www.itreetools.com). Core information measured included tree size, health, location type, and adjacent land use (Table 1). To assess the impact of current planting initiatives on the street tree population in West Oakland, we monitored all street trees in the study plot annually from 2007 to 2011. Field work took place in Jun.–Oct. each year. During the monitoring years, we recorded newly planted trees and status of previously observed trees. Tree status was recorded as removed, standing dead, or alive. Trees marked alive or standing dead were retained in the dataset for monitoring checks the following year. Standing dead status was defined by the absence of any green leaves and live buds. Additional details about field methods, including quality assurance/quality control and logistical concerns, are found in Appendix 1.

For this study, we used a restrictive definition of street trees: only trees in sidewalk cut-outs and planting strips, plus trees in medians, were included for monitoring. Only planting strip locations along the street side of the sidewalk were included. Some additional trees in lawns within the right-of-way or planting strips adjacent to buildings were in the 2006 inventory, but inconsistencies regarding whether those trees were included in 2006 prevented the inclusion of those planting location types in the monitoring study.

## Data analysis

### *Demographic equations, mortality rates, and population growth*

Annual tree counts and mortality observations were used to calculate the elements of the street tree demographic balancing equations, and to determine annual mortality rate and population growth. The classic balancing equation (Preston et al. 2001) demonstrates how population size changes over time with the addition of individuals

**Table 1** Street tree inventory data used in the monitoring study. Category definitions for health condition, land use, and location site generally followed i-Tree Streets (formerly STRATUM) (www.itreetools.com)

| Variable | Description |
|---|---|
| Diameter at breast height (DBH) | Stem diameter (cm) at 1.37 m from ground; for multi-stem trees, the quadratic mean of observed stems was used |
| DBH size class | 0.1–7.6, 7.7–15.2, 15.3–30.5, 30.6–45.7, 45.8–61.0, >61.0 cm[a] |
| Health condition rating | Numeric code for the health of the tree, with separate ratings for wood (structural health) and leaves (functional health): dead or dying (extreme problems), poor (major problems), fair (minor problems), good (no apparent problems) |
| Land use | Land use of buildings adjacent to the tree: single-family residential, multi-family residential, industrial/large commercial, park/vacant/other, small commercial |
| Location site | Type of planting site where the tree is located: planting strip, sidewalk cut-out, or median[b] |

[a] DBH size classes generally followed Nowak et al. (2004); however, the largest size classes defined in that study were combined here due to small sample sizes. In logistic regression models, the largest size classes were further collapsed, with >30.5 cm as the combined largest size class

[b] Other location site categories were included in i-Tree Streets but excluded from this study (e.g., lawns/yards)

through birth and in-migration, and the subtraction of individuals through death and out-migration (Table 2a, Eq. 1).

For street trees, applying the balancing equation requires modifications in both calculation and conceptualization. While the classic balancing equation (Table 2a, Eq. 1) is traditionally applied to a population of the same species, the street tree balancing equations (Table 2b, Eqs. 2 and 3) include the entire community of trees, with multiple species. Other authors have used the term "street tree population" to describe all street trees in a given area (McPherson and Rowntree 1989; McPherson and Simpson 2002; McPherson 2003). We follow that convention while acknowledging that street tree populations are anthropogenically-constructed systems with multiple species.

The street tree population in West Oakland is an open system: trees enter through planting and leave through removal (Fig. 1). In this study system, we observed no natural recruitment of new seedlings. The pool of street trees at any particular census $T$ included both living trees, $N_A$ ($T$), and standing dead trees, $ND$ ($T$) (Fig. 1). Consider the pool of live trees observed at year $T$. At the next monitoring check, $T$+1, those trees are either still alive $Survived[T,T+1]$, standing dead ($Died[T,T+1]$), or removed/missing ($Removed_A$ $[T,T+1]$). Newly planted trees are added in through $Plant_A$ $[T,T+1]$; this specifically refers to newly planted trees that are observed alive

**Table 2** (a) Classic demographic balancing equation and associated terms. (b) Demographic balancing equation adapted for a street tree population; Eq. 2 balances the live trees and Eq. 3 balances the standing dead trees

| Term | Definition |
|---|---|
| (a) | |
| $N(T+1)=N(T)+B[T,T+1]-D[T,T+1]+I[T,T+1]-O[T,T+1]$ | |
| | (Eq. 1, after Preston et al. 2001, Eq. 1.1) |
| $N(T)$ | Number of individuals alive at time $T$ |
| $B[T,T+1]$ | Number of births between $T$ and $T$+1 |
| $D[T,T+1]$ | Number of deaths between $T$ and $T$+1 |
| $I[T,T+1]$ | Number of in-migrations between $T$ and $T$+1 |
| $O[T,T+1]$ | Number of out-migrations between $T$ and $T$+1 |
| (b) | |
| $N_A(T+1)=N_A(T)+Plant_A[T,T+1]-Died[T,T+1]-Removed_A[T,T+1]$ (Eq. 2) | |
| $N_D(T+1)=N_D(T)+Plant_D[T,T+1]+Died[T,T+1]-Removed_D[T,T+1]$ (Eq. 3) | |
| $N_A$ ($T$) | Number of trees alive at time $T$ |
| $N_D$ ($T$) | Number of trees standing dead at time $T$ |
| $Plant_A$ $[T,T+1]$ | Number of new planted trees between $T$ and $T$+1 that are observed alive at $T$+1 |
| $Plant_D$ $[T,T+1]$ | Number of new planted trees between $T$ and $T$+1 that are observed standing dead at $T$+1 |
| $Died[T,T+1]$ | Number of trees alive at time $T$ that are observed standing dead at $T$+1 |
| $Removed_A$ $[T,T+1]$ | Number of trees alive at time $T$ that are observed removed/missing at $T$+1 |
| $Removed_D$ $[T,T+1]$ | Number of trees standing dead at time $T$ that are observed removed/missing at $T$+1 |
| $Survived[T,T+1]$[a] | Number of trees alive at time $T$ that are observed alive at $T$+1 |
| $StillDead[T,T+1]$[a] | Number of trees standing dead at time $T$ that are observed standing dead at $T$+1 |

[a] Although $Survived[T,T+1]$ and $StillDead[T,T+1]$ are not used in Eqs. 2 and 3, they help to illustrate the balancing equations in Fig. 1

$T$ is time (years)

at time *T+1*. These changes in the pool of live trees are encapsulated in the modified balancing equation (Table 2, Eq. 2).

The annual mortality rate, *AMR*, from *T* to *T*+1 is:

$$AMR[T,T+1] = \frac{Died[T,T+1] + Removal_A[T,T+1]}{N_A(T)} = 1 - \frac{Survived[T,T+1]}{N_A(T)}$$

(Eq. 4, after Sheil et al. 1995 Eq. 6)

Previous urban forest studies have similarly combined dead and removed (i.e., "missing") trees in the definition of mortality rate (Nowak et al. 2004; Lu et al. 2010; Roman and Scatena 2011). To calculate annual mortality rate, only the observed status at each census was relevant. It is unknown whether trees represented by $Removed_A$ [*T*,*T*+1] were removed while still alive, or removed after dying. Additionally, the annual mortality rate, as defined here, includes only live trees from time *T* in the denominator; Nowak et al. (2004) calculated mortality rates of re-censused urban forest plots in Baltimore, MD in the same manner.

Next, consider the pool of standing dead trees observed at year *T*. Some of these trees were removed by the next census ($Removed_D$ [*T*,*T*+1]), and the rest remained in the landscape as standing dead trees (*StillDead*[*T*,*T*+1]). Newly planted trees observed at time *T*+1 were added to the dead tree pool if they were standing dead during summer field work *PlantD* [*T*,*T*+1]. Presumably all new trees were alive when they were put in the ground, but by the summer monitoring check, a few had already died.

The change in live street tree counts is referred to as the population growth rate. As with the demographic balancing equation, methods are rooted in population biology of natural systems. The intrinsic population growth rate $\lambda$ and the annual population growth rate $\lambda_T$ (Table 3, Eq. 5) are central to demographic models (Silvertown et al. 1993; Morris and Doak 2002). In count-based population viability analysis, the arithmetic mean of the log

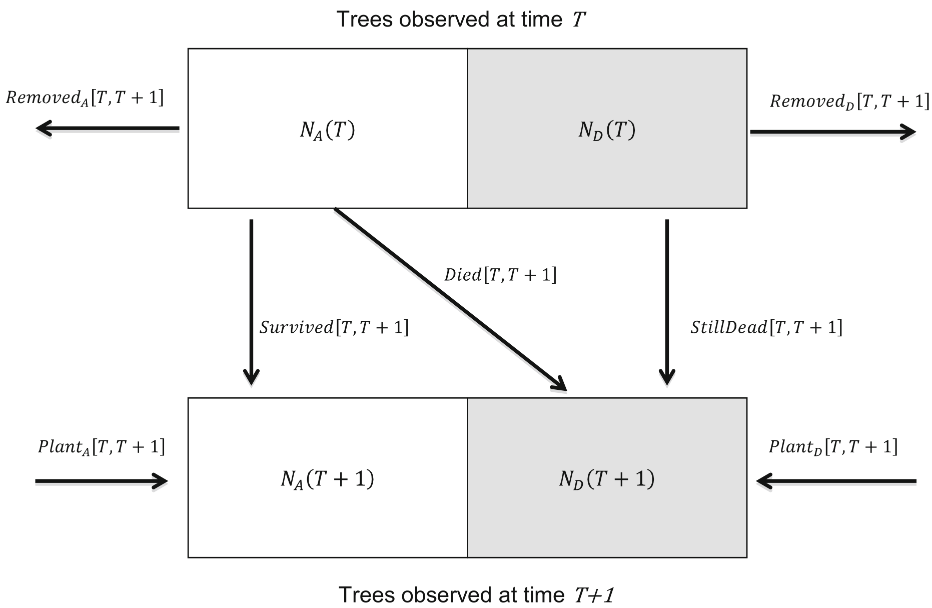


**Fig. 1** Diagram illustrating street tree balancing equations for live and standing dead street trees (Table 2, Eqs. 2 and 3). Terms are defined in Table 2

population growth rate, $\mu$, is used to assess population trends and predict extinction risk (Morris and Doak 2002). Population trajectories will tend to grow when $\mu$>0 and $\lambda$>1, while trajectories will tend to decline when $\mu$<0 and $\lambda$<1. The variance of the log population growth rate is given by $\sigma^2$, a measure of the year-to-year variability in population counts (Morris and Doak 2002, Eq. 3.9). We calculated the estimates of $\mu$ (Table 3, Eq. 6) and $\sigma$2 using annual counts of live street trees. In this study, the population count-based approach was strictly used to describe observed trends in the street tree population, and not to project future changes in population size.

We also calculated three other informative metrics from the annual tree censuses (Table 4, Eqs. 7–9). These metrics—proportion standing dead, proportion standing dead removed, and proportion of newly planted live trees among total live trees—complement the classically-defined mortality rate and population growth rate, and they help to summarize observations of tree death, removal, and planting in the population.

*Mortality and survivorship curves*

To assess the shape of the street tree mortality curve, we used size-based mortality rates for the 5-year (2006–2011) observation period. Diameter at breast height (DBH) size class bins were organized similar to Nowak et al. (2004) (Table 1). The value *Survived*[2006, 2011] represents the number of trees that were alive in 2006 which survived to census 2011. The annual mortality rate based on census data from 2006 and 2011 is:

$$AMR[2006, 2011] = 1 - \left(\frac{Survived[2006, 2011]}{N_A(2006)}\right)^{\left(1/5\right)}$$

(Eq. 10, after Sheil et al. 1995 Eq. 6)

Mortality rates were calculated separately for each DBH size class to create the mortality curve. Note that this formula is simply an extension of Eq. 4, which was only applicable to 1-year time intervals. Previous forest ecology studies reporting mortality curves have used a wide range of interval periods (e.g., 1–21 years in Lines et al. 2010).

A subset of the initial 2006 inventory was used to create this size-based mortality curve. Palm trees were not relevant to this mortality curve because their DBH size class is not meaningfully related to health or age. *Cupressus sempervirens* was also excluded because of inaccessible DBH due to tree growth form. Trees lacking DBH information in the 2006

**Table 3** Formulae and terms for the population growth rate. The relationships here are used in density-independent count-based models of population viability (Morris and Doak 2002). In the context of this urban forestry study, $\lambda_T$ is interpreted as the annual street tree population growth rate. To calculate $\hat{\mu}$ and $\hat{\sigma}^2$, the number of live trees at time $i$, $N_{Ai}$, was used for all places where simply $N_i$ is used here. The total number of census counts is $q$+1

| Term | Definition |
|---|---|
| $\lambda_T$ | Annual population growth rate<br>$N(T+1)=\lambda_T N(T)$<br>(Eq. 5, after Morris & Doak 2002, Eq. 2.1) |
| $\hat{\mu}$ | Estimated value of $\mu$, the arithmetic mean of the log population growth rate<br>$\hat{\mu} = \frac{1}{q}\sum_{i=0}^{q-1} \ln(N_{i+1}/N_i)$<br>(Eq. 6, after Morris and Doak 2002, Eq. 3.9) |

**Table 4** Supplemental metrics of population change for street trees. These metrics summarize observations about tree deaths, removals, and plantings

| Term | Definition |
|---|---|
| Proportion standing dead [*T*] | $\frac{N_D(T)}{N_A(T)+N_D(T)}$ (Eq. 7) |
| Proportion standing dead removed [*T*,*T*+1] | $\frac{Removed_D[T,T+1]}{N_D(T)}$ (Eq. 8) |
| Proportion of newly planted live trees among the total number of live trees [*T*] | $\frac{Plant_A[T,T+1]}{N_A(T)}$ (Eq. 9) |

database and trees omitted by field crews from the 2006 inventory were also excluded from the mortality curve (Appendix 1). Multi-stem trees were included in the mortality curve, with the geometric mean of recorded stems used for size class categorization (sensu Nowak et al. 2004).

We also calculated age-based survivorship for newly planted trees observed during the monitoring years 2007–2011 to quantify tree survival during the establishment period. All new street trees observed during census *T* were treated as an even-aged cohort. Although the trees were not planted at precisely the same time, complete planting records were unavailable, and for simplicity we lumped them into cohorts according to the year of first observation.

*Association between 5-year survival and selected risk factors*

To analyze the association between of several potential risk factors and tree survival, we constructed logistic regression models. The outcome of interest was 5-year tree survival (2006–2011), and the potential explanatory variables were DBH size class, foliage health condition, wood health condition, planting location site, and land use recorded in 2006 (Table 1). These risk factors were selected because they are commonly recorded items in most street tree inventories, and they have been previously connected to mortality (Nowak et al. 2004; Lu et al. 2010; Lawrence et al. 2011). We used a subset of the original inventory for the regression model; only trees with complete data for all risk factors were considered. In addition to the exclusion reasons listed above for the size-based mortality curve, a few trees that lacked 2006 health condition were also excluded.

Multivariate logistic regression models for mortality or survival enable interpretation across a range of risk levels, and for the incorporation of interactive effects (Jewell 2004). Logistic regression is commonly used to study binary outcomes in epidemiology for human populations, such as death and disease occurrence (Hosmer and Lemeshow 2000; Jewell 2004), and tree mortality in wildland forests (e.g., Das et al. 2007; Lines et al. 2010). We built models using the logit function in Stata 11 (StataCorp 2009). The general form of a multivariate logistic regression model, expressed as the logit function, is:

$$\log\left(\frac{p_{x,y}}{1-p_{x,y}}\right) = a + bx + cx$$

(Eq. 10, after Jewell 2004 Eq. 14.2)

where *X* and *Y* represent independent risk factors, and $p_{x,y}$ is the probability of survival given that those risk factors take on particular values. For ordinal variables (DBH size class and health condition rating), the coefficient *b* is interpreted as the log odds ratio (OR) of a unit increase in *x*, holding *c* fixed. The odds ratio is a measure of effect size, describing the strength of association between the explanatory variable and the outcome (see Jewell 2004).

For nominal variables (location site and land use), indicator ("dummy") variables were used (Hosmer and Lemeshow 2000; Jewell 2004), with one category selected as baseline and compared against the other categories. In these cases, the coefficient is interpreted as the log odds comparing a given category to the baseline (baselines for the final model are provided in Table 7a). Survival was used as the outcome of interest, as opposed to mortality, for ease of interpreting odds ratio results.

For model building, we used an iterative process to compare nested models with likelihood ratio tests; the final model had the highest likelihood, corrected for degrees of freedom (Hosmer and Lemeshow 2000; Jewell 2004). We also used likelihood ratio tests to evaluate the use of indicator variables for DBH size class and health condition. Indicator variables may be appropriate if mortality risk does not change linearly as size class or health condition increases (Jewell 2004). We considered multiplicative interaction between health condition and size class, because small trees are more susceptible to stress and injury (Richards 1979; Miller and Miller 1991). This specific interaction was included based on field observations and plausible mechanisms for interaction; interactions between other explanatory variables are possible but were not considered.

The fit of the final model was evaluated with two diagnostics: the Hosmer-Lemeshow goodness-of-fit test and the receiving operator characteristic (ROC) curve. The Hosmer-Lemeshow test divides the sampled individuals into categories of predicted risk, using a Pearson $X^2$ to compare predicted and observed risk (Hosmer and Lemeshow 2000; Jewell 2004). For this test, a small $p$-value indicates lack of fit (Hosmer and Lemeshow 2000; Jewell 2004). The area under the ROC curve was used to assess model discrimination, where 0.5 indicates no discrimination, 0.7–0.8 indicates acceptable discrimination, 0.8–0.9 indicates excellent discrimination, and >0.9 indicates outstanding discrimination (Hosmer and Lemeshow 2000).

## Results

### Demographic equations, mortality rates, and population growth

The total number of live street trees in the plot increased from 995 in 2006 to 1166 in 2011 (Table 5a); this is a net increase of 171 trees, or 17.2 %. Live tree counts from 2006 included 31 trees that were assumed to have been omitted from the initial inventory records (Appendix 1). Of the 995 live trees in 2006, 822 survived to 2011, for an annual mortality rate of 3.7 % (Eq. 10).

The annual population growth rate was positive each year during the study period, with low variance ($\hat{\mu} = 0.0317,\ \hat{\sigma}^2 = 0.0004$, Table 5a). A total of 401 new live trees were recorded from 2007 to 2011, with an average of 80 new live trees per year (Table 5a). Based on the modified balancing equations, the annual mortality rate during the study period ranged from 2.3 to 10.3 % (Table 5a, Eq. 4). The average annual proportion standing dead was 1.7 %. Of the standing dead trees observed during census $T$, an average of 56.7 % were removed by the next census (Table 5b).

Among the 995 live trees in 2006, the most common species were *Platanus x acerifolia* (12.06 %), *Magnolia grandiflora* (10.75 %), *Prunus cerasifera* (10.35 %), *Pyrus calleryana* (7.49 %), *Pyrus kawakamii* (6.53 %), and *Fraxinus oxycarpa* (6.43 %). All other species represented <5 % of the live tree pool in 2006. We present the species information as a description of our baseline inventory; however, species was not included in our analysis because of the wide assortment of different species included, and clustering of certain species in different size classes, making it difficult to include species meaningfully in the models.

**Table 5** Annual street tree counts in West Oakland: a) live tree counts, annual mortality rates, and population growth rates, and b) standing dead tree counts, proportion standing dead during each census, and proportion of standing dead trees removed each interval. The demographic balancing equation terms are defined in Table 2, and $\hat{\mu}$ is defined in Table 3 (Eq. 5). The annual mortality rate (Eq. 4) is defined in the text. The proportion standing dead (Eq. 7) and proportion standing dead removed (Eq. 8) are defined in Table 4

| year, $T$ | a) | | | | | | | b) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Live trees, $N_A$ ($T$) | *Died* $T,T+1$ | $Removed_A$ [$T,T+1$] | $Plant_A$ [$T,T+1$] | $\frac{Plant_A[T,T+1]}{N_A(T)}$ | Annual mortality rate, *AMR*[$T,T+1$] | $\ln\left(\frac{N_A(T+1)}{N_A(T)}\right)$ | Standing dead trees, $N_D$ ($T$) | Proportion standing dead [$T$] | *Died*[$T,T+1$] | $Removed_D$ [$T,T+1$] | $Plant_D$ [$T,T+1$] | Proportion standing dead removed [$T,T+1$] |
| 2006 | 995 | 18 | 84 | 139 | 0.1347 | 0.1025 | 0.0365 | 5 | 0.0050 | 18 | 3 | 5 | 0.6000 |
| 2007 | 1032 | 17 | 28 | 48 | 0.0464 | 0.0436 | 0.0029 | 25 | 0.0237 | 17 | 15 | 0 | 0.6000 |
| 2008 | 1035 | 8 | 21 | 54 | 0.0509 | 0.0280 | 0.0239 | 27 | 0.0254 | 8 | 15 | 0 | 0.5556 |
| 2009 | 1060 | 7 | 17 | 78 | 0.0700 | 0.0226 | 0.0497 | 20 | 0.0185 | 7 | 9 | 1 | 0.4500 |
| 2010 | 1114 | 4 | 26 | 82 | 0.0703 | 0.0269 | 0.0456 | 19 | 0.0168 | 4 | 12 | 0 | 0.6316 |
| 2011 | 1166 | n/a | n/a | n/a | n/a | n/a | n/a | 11 | 0.0093 | n/a | n/a | n/a | n/a |
| | | | | | | | $\hat{\mu} = 0.0317$ | | | | | | |
| | | | | | | | $\hat{\sigma}^2 = 0.0004$ | | | | | | |

## Mortality curves and young tree survivorship

A subset of 940 live trees from 2006 was used to construct the size-based mortality curves (94 % of the total live trees in 2006). Excluded trees were 12 palms, 2 *Cupressus sempervirens*, and 41 trees missing the 2006 DBH measurement. For this subset of trees, the annual mortality based on the 2006–2011 observation interval was 3.8 % (Eq. 10). The street trees in this neighborhood generally followed a Type III mortality curve, with 5.6 % annual mortality for the smallest size class, 0.8–1.6 % for mid-size trees, and 0 % for the largest size class (Fig. 2). The smallest size class also constituted a majority (61 %) of the trees in the mortality curve (Fig. 2).

Survivorship data for the newly planted trees observed in monitoring years 2007–2011 (Table 6) shows high mortality in the first few years after planting. Averaging across the cohorts, typically 99 % of new trees were observed alive during their first census, 91 % survived 1 year after they were first observed, 83 % survived 2 years, and 75 % survived 3 years.

## Association between 5-year survival and selected risk factors

The final logistic regression model (n=924, 93 % of the total live trees in 2006) included explanatory variables DBH size class, foliage health condition, planting location site, and an interaction term for DBH size class and foliage condition (Table 7a). Diagnostic evaluations indicated that the final model had acceptable discrimination (area under ROC curve= 0.7648) and no evidence of lack of fit (Hosmer-Lemeshow goodness-of-fit $p$-value=0.2112).

Larger trees and those with better foliage health ratings had higher survival over 5 years. Trees in sidewalk cut-outs had higher survival compared to planting strips. The three largest DBH size class categories (Table 1) were combined due to the absence of deaths in the largest size classes; zero cells in contingency tables are commonly collapsed in logistic regression due to challenges in estimating odds ratios (Hosmer and Lemeshow 2000).

The multiplicative interaction term allowed for assessment of survival outcomes at varying levels of size class and foliage condition (Table 7b). Foliage condition was strongly associated

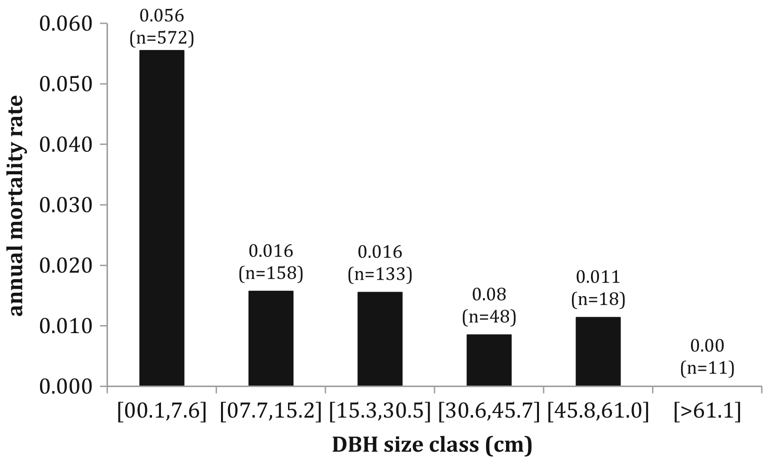


**Fig. 2** Size-class mortality curves for West Oakland street trees, using annual mortality calculated from the 2006–2011 observation interval (Eq. 10). Total $n$=940

**Table 6** Survival fate of new planted street trees, observed during annual monitoring 2007–2011. All new street trees observed during census *T* were treated as an even-aged cohort. Although the trees were not planted at precisely the same time, for simplicity we lumped them into cohorts according to the year of first observation. Under each year *T* are the numbers of new trees from that cohort observed alive during subsequent censuses. In parentheses is the proportion surviving out of the total number planted in that cohort

| | Year, *T* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2007 | | 2008 | | 2009 | | 2010 | | 2011 | | average |
| Total # new trees in year *T* | 144 | | 48 | | 54 | | 79 | | 82 | | |
| # live new trees in year *T* | 139 | (0.9653) | 48 | (1.0000) | 54 | (1.0000) | 78 | (0.9873) | 82 | (1.0000) | 0.9905 |
| 1 yr. later | 128 | (0.8889) | 41 | (0.8542) | 54 | (1.0000) | 71 | (0.8987) | | | 0.9104 |
| 2 yrs. later | 116 | (0.8056) | 37 | (0.7708) | 50 | (0.9259) | | | | | 0.8341 |
| 3 yrs. later | 109 | (0.7569) | 36 | (0.7500) | | | | | | | 0.7535 |
| 4 yrs. later | 105 | (0.7292) | | | | | | | | | |

with survival for the smallest size class ($\widehat{OR} = 2.298$, $p<0.001$). However, for mid-size and larger size classes, foliage condition was not significantly related to survival. DBH size class was significantly associated with survival across all foliage conditions, but the relationship was stronger (higher $\widehat{OR}$) for trees in the dying and poor health condition ratings.

## Discussion

The West Oakland street tree population grew during the study period, with additions from new plantings exceeding losses from removals and deaths. However, the rate of growth was constrained by high morality of young and small trees. Many new young trees died or were removed during the first few years after planting (Table 6). This observation is complemented by the relatively high mortality rate for trees in the smallest size class (Table 2). The size-based mortality curve for West Oakland street trees has a Type III shape (Fig. 2; Harcombe 1987), unlike the U-shaped mortality trend seen in Syracuse (Nowak 1986; street trees only) and Baltimore (Nowak et al. 2004; street, yard and park trees). It is possible that different cities and segments of the urban forest have different mortality curve shapes. However, compared to the Baltimore and Syracuse studies, the West Oakland plot also had very few large trees. If only one of the 11 large trees in our Oakland study had died over the 5-year study period, the mortality curve would have been U-shaped. Additional long-term data is needed to assess the conditions under which urban trees exhibit U-shaped and Type III mortality curves. Determining the shape of the urban tree mortality curve is important for population projections and monetization of ecosystem services (McPherson et al. 2008; Morani et al. 2011).

Our analysis of changing population size over time was rooted in the classic demographic balancing equation (Preston et al. 2001). The street tree balancing equations (Table 2, Fig. 1) provided a conceptual framework to summarize transitions in the population, separating the pools of living and standing dead trees. The live street tree population in West Oakland was in a continual state of flux during the study period. Large inputs of new young trees every year were necessary to out-pace mortality losses. These findings provide quantitative support for Richards' (1979) assertion that young tree death drives urban tree population

**Table 7** Final logistic regression model for 2006–2011 tree survival (n=924), with estimated odds ratios (OR) and 95 % confidence intervals (CI) for each parameter: a) overall model results, and b) varying odds ratio estimates across levels of DBH size class and leaves health due to interaction term. Parameters from the 2006 inventory are defined in Table 1

| Parameter | OR estimate | 95 % CI | *p*-value | Baseline |
|---|---|---|---|---|
| a) | | | | |
| DBH size class | 12.093 | 3.646, 40.108 | <0.001 | Smallest size class, 0.01–7.6 cm |
| Foliage condition | 2.298 | 1.870, 2.822 | <0.001 | Lowest health condition (dying) |
| Location site | | | | Planting strip |
| Cut-out | 1.614 | 1.093, 1.472 | 0.016 | |
| Median strip | 0.509 | 0.176, 1.472 | 0.212 | |
| Interaction: DBH size class * foliage condition | 0.522 | 0.334, 0.816 | 0.004 | |
| b) | | | | |
| OR for a unit increase in DBH size class when leaves health level is: | | | | |
| Dying | 12.093 | 3.646, 40.108 | <0.001 | |
| Poor | 6.316 | 2.895, 13.777 | <0.001 | |
| Fair | 3.298 | 2.163, 5.030 | <0.001 | |
| Good | 1.723 | 1.175, 2.526 | 0.005 | |
| OR for a unit increase in foliage condition when DBH size class (cm) is: | | | | |
| [0.01,7.6] | 2.298 | 1.870, 2.822 | <0.001 | |
| [7.7,15.2] | 1.200 | 0.777, 1.853 | 0.411 | |
| [15.3,30.5] | 0.627 | 0.266, 1.476 | 0.285 | |
| [>30.5] | 0.327 | 0.090, 1.195 | 0.091 | |

cycles. Researchers have previously suggested that an adequate proportion of young/small trees is needed for population stability (Richards 1983; McPherson and Rowntree 1989; Maco and McPherson 2002). In this neighborhood, the large proportion of small trees (61 % of trees in smallest size class 2006), coupled with very high mortality of young (Table 6) and small (Fig. 2) trees, suggests vulnerability to population crashes if planting efforts slow down. New live trees accounted for an average of 7.4 % of the total live tree population every year (Table 5a). As Clark et al. (1997) explained, "sustainable urban forests require human intervention"; this is especially true for street tree populations, as they are constructed by human-driven cycles of planting and removal.

A thorough evaluation of site conditions and maintenance problems was beyond the scope of this research, but such data might offer more direct evidence for causal mechanisms of tree death. The persistence of standing dead trees in the landscape (Table 5b) may indicate slow follow-up to remove and replace dead trees. It is possible that financial resources would be better spent planting fewer trees, and investing more heavily in site modifications and tree care during the establishment phase (Richards 1979; Miller and Miller 1991), to prevent high mortality of young trees. The net increase in population counts and anticipated ecosystem services would be enhanced by lowering young tree mortality rates.

To assess the association between selected risk factors and 5-year survival outcomes in West Oakland, we used multivariate logistic regression models (Jewell 2004; Hosmer and Lemeshow 2000). During model building, variables that were not significant (land use, wood health condition) were discarded. Significant explanatory variables in the final model were DBH size class, foliage health condition, planting location, and a multiplicative interaction term between size class and foliage condition (Table 7a). Both DBH size class and foliage condition were treated linearly in the final model, without indicator variables. Without the interaction term, a linear trend in log odds risk for foliage condition did not describe the pattern effectively, and indicators should be used. However, with the interaction term, the simpler model without indicator variables for foliage condition was adequate (results not shown).

Trees that were small and had poor foliage condition in 2006 were less likely to survive to 2011. These results are consistent with previous findings for urban trees in Baltimore, MD (Nowak et al. 2004), although health condition was not separated by foliage and wood in that study. The interaction term allowed a closer inspection of the relationship between size class and foliage (Table 7b). Increasing DBH size class was significantly associated with increased survival across all foliage ratings, with the largest odds ratio for trees with foliage categorized as dying. However, the association between health condition and survival was only significant for the smallest size class. In other words, for mid-size and large trees, there was no significant relationship between foliage condition and survival. There are two possible explanations for this observation. First, relative to large trees, small trees are more susceptible to stress and injury (Nowak et al. 2004), including inadequate maintenance, accidents, and vandalism. Richards (1979) suggested that establishment-related losses are unique to young and small trees, before they have grown sufficiently to withstand minor injuries. Second, while large tree removal requires trained personnel and equipment (Harris et al. 2004; Smiley et al. 2007), small tree removal is relatively easy. Small trees could have been removed by neighbors due to concerns for tree health or dissatisfaction with tree appearance. Note that in our study and in other urban forest research (Nowak et al. 2004; Lu et al. 2010; Roman and Scatena 2011), mortality is a combination of trees observed standing dead and those observed missing or removed.

In terms of planting location, trees located in sidewalk cut-outs were more likely to survive than those located in planting strips, with no significant difference for median trees (Table 7a). For newly planted street trees in New York City, trees in lawns had higher survival than trees in sidewalks, but soil pit area for sidewalk trees did not have a significant effect on mortality (Lu et al. 2010). The explanation for higher survival of sidewalk cut-out trees in West Oakland is unclear. In this neighborhood, both cut-outs and planting strips provide little space for growing trees (common width 0.6–0.9 m). It is possible that the effect of planting location was confounded by risk factors that were not included in the model.

The small study plot used in this case research may limit the ability to make generalizations to other street tree populations. Different mortality patterns may be observed in neighborhoods with different socioeconomic classes (Nowak et al. 1990), planting programs, maintenance regimes, species composition, and baseline proportions of small trees. However, the annual mortality for West Oakland trees (3.7 %) is within the range of typical annual street tree mortality (3.5–5.1 %) from a meta-analysis of other studies (Roman and Scatena 2011), which indicates that overall mortality rates were not unusual. Other limitations to our study include potential bias from trees with incomplete information for inclusion in the size-based mortality curves and logistic regression models, and from our method of incorporating trees that were assumed omitted in the 2006 inventory (Appendix 1). Additionally, annual censuses may have missed “ghost mortalities” (sensu Sheil 1995; van Mantgem and Stephenson 2005)—trees that were planted and removed between observations. Lastly, the effect size for responses with large confidence intervals should be treated with caution (Table 7). For some strata in our analysis, small sample sizes within strata of categorical explanatory variables may have contributed to uncertainty reported in the odds ratio (Greenland et al. 2000).

This case study provides a conceptual and methodological framework for future urban tree mortality research. The street tree balancing equations, metrics of population transitions, mortality curves, and multivariate models can be replicated in other cities and neighborhoods, and adapted to other segments of the urban forest. To the best of our knowledge, there is only one previously published study with multi-year street tree monitoring data across all size classes (Boyce 2010), conducted by a neighborhood association. Collaboration and data sharing between urban forest researchers and local practitioners should be enhanced to improve our collective understanding of urban tree population dynamics. Long-term tree monitoring (Baker 1993; McPherson 1993; Pauleit et al. 2002; Brack 2006; Cumming et al. 2008) and longitudinal data are needed to assess the impact of urban forest planting programs in the context of on-going mortality. To gather comprehensive monitoring and mortality data on urban trees, it is essential that urban foresters and urban ecologists coordinate our efforts, partnering with local practitioners and learning from the experiences of forest ecologists working in long-term monitoring programs (Condit 1995; Sheil 1995; Smith 2002; McRoberts et al. 2005; Lindenmayer and Likens 2009, 2010).

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## Appendix 1: Supplementary field data collection details

Several quality assurance and quality control steps were necessary to adapt the 2006 inventory system to multi-year monitoring. Some trees that were assumed to have been omitted from the 2006 inventory were retroactively added as alive in 2006. In these cases, tree size (>10 cm DBH in 2008) was taken as evidence that they were already in the ground in 2006. The urban forestry initiatives in this neighborhood plant small saplings, therefore it seemed reasonable to assume that mid-size and large trees were omitted in 2006. In the first monitoring year (2007), we also confirmed species, land use, and planting location information from the initial inventory, correcting errors where necessary.

Standing dead status during monitoring years 2007–2011 was defined by an absence of green leaves and live buds. This is a lower threshold of health than the "dead or dying" condition rating in i-Tree (Table 1). Trees from the 2006 inventory recorded as health rating 1 (dead or dying) for both foliage and wood were categorized as standing dead by our definition. However, because health rating is subjective, and different individuals were involved during the inventory vs. monitoring years, this approach to connect our standing dead definition and 2006 health categories was imprecise. There were 2 trees from the 2006 inventory with dying health ratings for foliage and wood that we recorded alive in 2007; however, we also noted that these trees were nearly dead. For simplicity in this analysis, because no backwards transitions were allowed from standing dead to alive, we retroactively re-categorized those 2 trees as alive in 2006.

To facilitate ease of finding trees each year in the study, tree location was recorded with several complementary systems: street addresses, manual notes on a map of GPS coordinates from the 2006 inventory, and order on the block. Tree order on the block was a system of numbering each tree every year in progression from north to south, or east to west, for one side of the street on a given block. The ordering system was used to facilitate database sorting for convenience during field work.

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