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Long-Term Tree Survival and Diversity of Highway Tree Planting Projects

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Abstract

Long-term, multi-decade research on planted tree survival in urban settings is sparse. One understudied urban environment is highway rights-of-way (ROW), lands adjacent to high-speed, unsignalized roadways. We conducted a re-inventory of tree planting cohort in northern Illinois, U.S. on a 48 km-long highway near Chicago which were 10-, 21-, and 30-years old to evaluate long-term patterns of survival and diversity. Using each randomly selected planting site along the highway as a unit of observation and analysis, we compared the number of trees documented in record drawing to the number of trees currently alive to determine percent survival. We evaluated 224 planting sites which originally contained 2,944 trees and collected data about the planting site location. For the oldest cohort, 26% of trees were still alive in 2018 (median survival by species = 16%, Q1 = 0%, Q3 = 48%), while 31% of the 21-year-old cohort (med. = 6%, Q1 = 0%, Q3 = 47%) and 86% of the 10-year-old cohort were still alive (med. = 85%, Q1 = 74%, Q3 = 96%). The survival of the 21- and 30-year-old cohort matches urban tree survival estimates by other researchers, while the 10-year-old survival is higher than expected. The only planting location characteristic that significantly affected survival was traffic islands (areas between the highway and entrance/exit ramps). Species with low drought tolerance were less likely to be alive for the 10-year-old cohort. Waterlogging tolerant species were more likely to be alive in the 10-year-old cohort. Since some species in the 21- and 30-year-old cohorts had very low survival, the tree species richness and diversity s in study areas declined between the initial record drawings and reinventory. This study demonstrates the challenges of maintaining long-term survival and diversity in the highway ROW and emphasizes the importance of species selection.

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Keywords

Drought tolerance; Roadside woody vegetation; Simpson diversity; Site conditions; Tree mortality; Tree planting initiatives

Introduction

Prompted by an increasing interest in the ecosystem services provided by urban trees, numerous large-scale tree planting initiatives are underway around the world (Pincetl, 2010; Campbell et al., 2014; UNECE, 2019; World Economic Forum, 2020). These efforts are not without challenges. Urban tree survival and condition are often compromised by poor soil conditions (Day and Bassuk 1994), time of planting (Miller and Miller, 1991), vandalism (Nowak et al., 1990), lack of post-planting care or stewardship (Boyce, 2010), construction activities (Hauer et al., 1994), lawn maintenance (Morgenroth et al., 2015), and disease and pest outbreaks (Herms and McCullough, 2014). These stressors limit which species can be supported in higher stress urban environments such as the roadside, consequently limiting their capacity for diversity (Sjöman et al., 2016). It is necessary to understand how the exposure of urban trees to environmental stressors and human activities affect the structure and composition of urban forests in order to effectively manage and sustain the urban forest's ability to provide benefits (Steenberg et al., 2017).

Beyond increasing the number of trees, there is also a strong emphasis in the urban forestry field to develop taxonomically diverse urban forests (Muller and Bornstein, 2010; Ordóñez and Duinker, 2013). One major goal for increasing taxonomic diversity in urban forests is to reduce the potential impacts of a pest or disease (Miller 1997). When an urban forest is dominated by a single species or genus, a pest or disease outbreak affecting those species could result in massive losses of urban canopy, such as have occurred with Dutch elm disease (Karnosky 1979) and Emerald Ash Borer (Davis Sydnor et al. 2011) in North America and elsewhere. Costs associated with such losses include the cost of tree removal, replacement, and lost ecosystem services. At the city-scale, urban forest diversity can directly influence ecosystem service provision and indirectly support continued ecosystem services by contributing to urban forest resilience (Morgenroth et al. 2016). Nevertheless, achieving a high degree of urban forest diversity has proven a difficult task as evidenced by multiple studies observing the dominance of a small number of taxa in cities and towns (e.g. Kendal et al. 2014; Cowett et al. 2017; Vander Vecht and Conway 2015).

Much of the urban forestry literature on planted tree survival has observed high variability in survivorship in general, which can vary with species (Koeser et al., 2013; Lawrence et al., 2012); time since planting (Roman et al., 2014a); maintenance practices such as irrigation, mulching, and removal of nursery stakes (Roman et al., 2014b); and neighborhood characteristics or land use (Nowak et al., 1990; Lu et al., 2010), among many other factors. However much of this research has focused on street trees, trees planted close to public roads and often found surrounded by pavement or planted in small areas of lawn (Nowak et al., 1990; Lu et al., 2010; Lawrence et al., 2012; Roman et al., 2014a, Roman et al., 2014b; Ko et al., 2015). Large scale tree planting projects also take place in other land use settings such as public greenspaces, institutional properties, and highway rights-of-way (ROW). Since planted tree survival can vary between different urban land uses (Nowak et al., 2004; Lu et al., 2010; Lawrence et al., 2012), it is necessary to examine patterns of survival and community composition in multiple urban settings.

Highway ROWs are the lands adjacent to high-speed, unsignalized roads, which are an important but understudied land use in the urban forest. Globally, there is an estimated 1 million km of highway (Meijer et al. 2018). The conterminous United States has an estimated 2 million hectares of unpaved ROW, 1-9% of which are estimated to contain woody vegetation (U.S. Department of Transportation and The Volpe Center 2010). In a survey of 12 North American cities, transportation and utility lands contained approximately 15% of the urban tree population (Nowak 2012). Moreover, transportation departments spend substantial funding on beautification efforts and can be responsible for planting large quantities of trees throughout a state (Khachatryan, et al. 2014; Blair, et al. 2019). For example, from 2008 to 2013 Florida Department of Transportation spent over $209 million (USD) on highway landscaping projects (Khachatryan et al. 2014). Trees in the highway roadside can provide services such as particulate air pollution mitigation (Janhäll 2015) and reduction of noise and the perception of environmental noise (Van Renterghem 2018) in addition to contributing to carbon sequestration (Fernandes et al. 2018; Rahman et al. 2015). The vegetated highway roadside can serve as habitat corridors for some animals (Encarnação and Becker 2015). Highways can also fragment habitats for many species or create ecological traps that attract wildlife to hazardous locations (Forman et al. 2002). At the same time, the highway roadside can be a stressful growing environment for trees because of poor soil conditions such as high pH, high bulk density, and low nutrient availability (Akbar et al. 2012; Chen et al. 2015; Claassen and Zasoski 1998; Haan, et al. 2012). Roadside trees can also be exposed to pollution (Werkenthin, et al. 2014) as well as de-icing road salt in cold-weather climates (Fay and Shi 2012; Cekstere and Osvalde 2013; Equiza et al. 2017). These conditions may limit tree survival and diversity in this environment, potentially limiting the benefits highway trees can provide. Indeed, an analysis of tree cover distribution in 35 megacities observed a lack of tree cover in areas near

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traffic corridors where woody vegetation could be beneficial for mitigating air pollution (Endreny, et al. 2020).

Studies on the survival of highway tree planting projects are limited and have focused on the first few years following planting. Six years after a highway landscaping project in Long Island, New York, U.S., tree survival varied widely between species, ranging from 3% for *Platanus* x *acerifolia* (Aiton) Willd. that were still alive and 57% for *Quercus rubra* Michx. (Highway Research Board 1961). In Florida, U.S., Blair et al. (2019) observed 98.5% of all study trees were still alive in the 9 to 58 months following planting next to highways, though this number does not account for replacements made during the first few years post-planting. Multiple management and site factors, such as distance to nearest pavement, the presence of drip irrigation, soil organic matter, and soil texture, affected the crown quality and vitality ratings of these highway trees in Florida. Roman et al. (2015) also observed high survival for a set of highway trees in Palo Alto, California (96% survivorship), though these trees were outside of a sound wall and were cared for by a non-profit organization. The lower survival in the Long Island study compared to the Florida and California could reflect changes over time in nursery, planting, and maintenance practices or differences in regional soil and climate. The highway ROW landscape can be a quite variable environment with a high degree of microtopography (Jimenez et al. 2013; Neher, et al. 2013). Construction modifications to topography can create cut-slopes and embankments with unfavorable growing conditions (Claassen and Zasoski 1998; Trammell et al. 2011; Bakr et al. 2015). The direction a slope is facing, its aspect, can also influence plant growth because of differences in available sunlight, soil temperature, and soil moisture (Forman et al. 2002). Additionally, many soil properties and stressors exhibit distance dependent relationships with the pavement edge (Bryson and Barker 2002; Akbar et al. 2012; Werkenthin, et al. 2014). Yet there is no clear research-based guidance available about tree placement in the highway ROW to reduce tree stress, increase survival, and consequently the benefits these trees can provide.

To better understand potential biophysical drivers of tree survival in the highway roadside, we conducted a re-inventory of three highway tree planting cohorts ranging in age from 10 to 30 years in order to evaluate long-term survival of trees planted next to a highway in northern Illinois, U.S.. We based our re-inventory on planting records and utilized each planting site as a unit of observation and analysis. Located at the border between temperate prairie and forest biomes, our study area can be a particularly challenging environment for establishing trees, making it even more important to study factors that affect long-term tree survival. Our research focuses on the survival and long-term diversity of planted trees since hundreds of millions of dollars (USD) and effort are put into similar large-scale tree planting efforts (Eisenman et al. 2021) even though potentially high mortality can lead to the costs of such projects outweighing potential benefits (Widney, et al. 2016). In particular, we examined factors relevant to the landscaping design process - location of trees within the ROW and species' tolerances for environmental conditions. These are factors that landscape architects, planners, arborists, and urban foresters use to guide decisions about what trees are planted in which locations. Yet there is no empirical evidence about the long-term effects of these decisions. Additionally, we evaluated long-term changes in tree community diversity to understand how planted diversity may change decades after planting.

Methods

Study Area

This study was conducted along a highway (Interstate 355 (I-355)) in the Chicago (United States) metropolitan region (41.932118°N, -88.037547°S to 41.538545°N, -87.960314°S; Figure 1). I-355 is a six-lane highway with average daily traffic volume of 271,980 cars per day. The roadway is 48 km long (Illinois State Toll Highway Authority, 2019) and runs primarily north to south. The northern portion of the highway was opened in 1989 (about 31.5 km long) while the southern section (16.5 km) was opened in 2007 (Illinois State Toll Highway Authority 2019). The northern portion of I-355 in DuPage County runs through a more densely developed region compared to the southern portion in Will County (DuPage County 2010 population density = 1,081 people per square km; Will County = 313 people per square km; United States Census Bureau 2019).

The study area has a temperate, continental climate with 94 cm average annual rainfall, 10°C average annual temperatures and daily extremes ranging from -32 to 40°C (Illinois State Climatologist 2007). The median growing season length is 177 days above 0°C (Illinois State Climatologist 2007). Northeastern Illinois soils formed on glacial deposits; most of DuPage and Will Counties' surficial geology consists of moraines and till plains (Calsyn 1999; Hanson 2004). The region lies at the intersection between Eastern broadleaf forests and tall grass prairie ecoregions with the distribution of these two ecosystems driven by landscape factors as well as natural and human disturbances (Fahey, et al. 2015).

Tree Planting Campaigns

We reviewed as-built landscaping plans that recorded the quantity and location of trees planted along 38.6 km of I-355 as part of three different planting campaigns in 1988, 1997, and 2008. As-built plans were provided by the Illinois State Toll Highway Authority and document the quantity and location of trees and other plants at planting sites following installation and verify that the project was completed according to the landscaping contract (or to document any deviations from the original design). We refer to the I-355 trees as part of three planting cohorts - 1988, 1997, and 2008 - based on the year each campaign began. Within each cohort trees were planted in stages. The majority of trees in these landscaping programs were planted from field grown nursery stock with excavated root balls wrapped in burlap (balled-and-burlapped or caliper trees; 77%). Approximately 13% of the trees were planted from containers. The stock type of the remaining trees was not indicated in the planting plans.

The 1988 and 1997 cohorts were planted in the northern portion of I-355 while the 2008 cohort was planted in the southern portion (Figure 1). The 1988 and 1997 planting sites in northern I-355 tend to be located closer to the highway, on steeper slopes, and between the highway and ramp (a traffic island) as compared to the 2008 planting sites in southern I-355 (Figure 2).

According to the landscaping record drawings, a total of 14,806 trees were planted along 38.6 centerline km of I-355 as part of landscaping activities in 1988, 1997, and 2008 (Table 21). Out of all the trees documented in the record drawings, approximately 13% of the 1988 cohort, 44% of 1997, and 27% of 2008 were evaluated as part of the long-term survival study.

Tree Survival Survey

To determine what proportion of planted trees from the three cohorts were still alive approximately 10, 21, and 30 years after planting, we re-inventoried a random selection of the landscaping trees in September and October of 2018 (Figure 3). The as-built planting records indicated the location and quantity of planting sites which contained same-species groupings of trees, usually ranging in quantity from around 5 to 50 trees in a site. The planting site was our unit of observation and analysis. In the context of this study, the planting site can also be considered analogous to a stand in forest ecology. Trees within these planting sites were typically 4.5 to 6 m apart and generally in rows no more than three deep. This approach prevents us from assessing performance at the scale of the individual tree since we did not have the exact location of each individual tree at the time of planting. This approach may also cause site-specific effects to over- or under-inflate survival. To create the most representative sample possible, we used GIS to randomly select 224 planting sites for inclusion in the survival assessment. Planting sites that were not readily or safely accessible were excluded from this analysis. We also adjusted our data analysis to account for site effects (see below).

We evaluated the long-term survivorship of each highway landscaping cohort by comparing the quantity of living trees at two time points: the year that the as-built records were approved and the reinventory year, 2018. Between the time of initial planting and the as-built records, usually one to three years, landscaping contractors would have replaced any trees that died. However, since replacement records are not available, our study only provides insight into survivorship after several decades in the landscape rather than survival in the first few years after planting. Our analysis treats each planting site as evenly aged, though it is possible for age to vary from one to three years within a planting site.

At each planting site, we documented the number of trees still present and confirmed their species. Trees present at the site were classified as living, poor quality (if 20% or less of foliage remained), or dead. The quantity of missing trees was calculated as the difference between the number of trees indicated on the planting records for a site and the number of trees present. These missing trees were categorized as dead for analysis purposes.

Additional Context Data

Additional site context data was collected at the tree planting sites and extracted from spatial data (ArcGIS v10, ESRI, Redlands, CA, United States) to test the potential effects of slope, aspect, distance from roads and elevation relative to the highway on survival (Table 1; Figure 4). For each planting site, we used a GPS unit (Trimble TDC100 Handheld Unit with R1 GNSS Receiver, Westminster, CO, USA) to record the center point of each planting site. Slope was measured at the middle and two edges of each planting site using a LaserAce 300 laser rangefinder (MDL, Aberdeen, Scotland, UK). Slope aspect, the compass direction of a slope face when the viewer is facing downslope, was recorded using a compass. Slope aspect was decomposed into northing and easting components (the cosine and sine of aspect, respectively) since aspect is a circular variable. A slope with northing equal to 1 faces north while a -1 northing faces south. Similarly, a slope with an easting of 1 faces east while a -1 easting slope faces west. Planting sites on flat ground were assigned northing and easting values of 0. We also recorded if the tree was located in a "traffic island," which we defined as a planting area located between the main highway and an entrance or exit ramp (example traffic island shown in Figure 4).

To measure the distance from the center of the planting site to the highway edge, an outline of the highway was created in GIS based on aerial photos of the study area (United States Department of Agriculture, 2017). The distance from the highway edge to the center of the planting area was then calculated using the proximity tool. Elevation of the planting site centers relative to the highway edge elevation was estimated based on regional light detection and ranging (LiDAR) data (Illinois State Geological Survey 2014) that was converted into a digital elevation model (DEM) with 1.2 m resolution. The average elevation in a 2 m radius around each GPS point and around the nearest edge of highway or side road was extracted from the DEM using the extraction tool. Elevation relative to the highway was calculated as the difference between the planting site and highway edge elevations.

Tree Species Environmental Tolerances

We included ratings of species' tolerances to drought, waterlogging, and shade in our inventory data set to investigate if certain environmental tolerances enhanced survival within our study cohorts. Species tolerance ratings were extracted from a ranking system developed by Niinemets and Valladares (2006). In this system species are ranked on a scale from 1 to 5 with 1 being very intolerant and 5 being very tolerant for each condition. *Acer* x *freemanii* A.E. Murray, *Malus* spp., *Acer miyabei* Maxim., and *Quercus robur* x *macrocarpa* tolerance data were not in Niinemets and Valladares (2006). However *A. freemanii* and *Malus* spp. tolerances had been estimated by Hirons and Sjöman (2019) using a procedure based on Niinemets and Valladares (2006), so these two species were included in the tolerance analysis. *Q. robur* x *macrocarpa* was excluded from analyses where tolerance ratings were included as predictors. Ratings were applied at the species level in instances where cultivars were specified in the as-built plans.

Data Analysis

We analyzed factors influencing highway tree survival using five different models:

1. Survival predicted by cohort,
2. Survival predicted by drought tolerance,
3. Survival predicted by shade tolerance,
4. Survival predicted by waterlogging tolerance, and
5. Survival predicted by site context and drought tolerance.

Each of the three environmental tolerance traits - drought, shade, and waterlogging tolerance - were evaluated using separate models since the three traits tend to covary with each other (Niinemets and Valladares 2006). For every model, each planting site with its percent survival for a particular species was a single observation. The 1997 cohort was excluded from Models 2 to 5 because of the substantially smaller sample size and small number of species. Models 2 to 5 were analyzed separately for the 1988 and 2008 cohorts since survival varied dramatically between the two cohorts and their planting sites are located in two distinct parts of I-355.

The models were fitted using a generalized linear mixed model (GLMM) with planting site as a random effect and a binomial distribution using the glmer( ) function from the lme4 package (Bates et al. 2015). The GLMM were fitted with a logit link function using a maximum likelihood approach with an adaptive Gauss-Hermite Quadrature method. Traffic island was coded as a binary variable indicating that a planting site was either located within a traffic island (between the highway and an entrance or exit ramp; 1) or not within a traffic island (0). Highway side was also coded as a binary variable indicating that a planting site was located on the northbound (0) or southbound (1) side of the highway. Potential covariation between site context model variables was evaluated using a variance inflation factor approach (VIF; Zuur, et al. 2007), though none of the models had problems with covariation (VIF < 3). Spatial correlation was not a problem for models according to an evaluation with Moran's I. The significance of the models was evaluated by comparing the log likelihoods of the full and null models (Zuur, et al. 2007). Variable significance was assessed with a chi-square test comparing the full and single-term deletion model. Model testing also used the area under curve (AUC) approach with a receiver operating characteristic curve (ROC) to assess the fit of the model. The closer AUC is to 1, the better the performance of the model to predict survival.

The change in planted tree diversity of each cohort from the time of the record drawings to 2018 was evaluated using three metrics: species richness (the number of species), evenness (the relative abundance of species), and diversity (an index reflecting both the number of species and evenness). Evenness was represented as Pielou's evenness (J'), calculated as

$$J' = \frac{-\sum_{i-1}^{S} \quad p_i ln ln\, p_i}{ln ln\, S} \qquad (1)$$

Where S is the total number of species and p_i is the proportional abundance of species i (Pielou 1975). A lower J' indicates low evenness or the dominance of a small number of species. While both the Shannon and Simpson diversity indices have been used to evaluate diversity of urban trees, we focused on the Simpson index because it is sensitive to evenness which is considered a desirable characteristic of urban forests (Cowett and Bassuk 2017). The Simpson index is

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sometimes reported as the Inverse Simpson Diversity Index (ISDI) for ease of interpretation since a high ISDI indicates high diversity (Sun 1992). Here we calculate and report the inverse value to facilitate comparison with other studies using the following equation:

$$ISDI = \frac{1}{\sum_{i=1}^{S} p_i^2} \quad (2)$$

Where S is the number of species and p_i is the proportional abundance of species i (Simpson 1949). Richness, evenness, and inverse Simpson was calculated based on the planting records for the surveyed study sites and based on observations of surviving trees in 2018 using the vegan package (Oksanen et al. 2019). Data were analyzed at the species level rather than cultivar. All analyses and graphing were conducted in R (R Core Team 2019) also using the tidyr (Wickham 2020), dplyr (Wickham et al. 2020), ggplot2 (Wickham 2016), ROCR (Sing et al. 2005), lmtest (Zeileis and Hothorn 2002), performance (Lüdecke et al. 2021), and DHARMa (Hartig 2021) packages.

Results

Overall Survival

Survivorship was significantly lower in the 1988 (26% alive) and 1997 (31%) cohorts compared to 2008 (86%) (Figure 5; Table 3 - Model 1). Of the surveyed trees, 6% were classified as likely construction removals - that is, trees removed because of construction activities - based on reviews of historic aerial photos (17% of trees in 1988, 1% in 1997, and 0.2% in 2008). In the 2008 cohort, 5% of surveyed trees were classified as poor quality - still alive but with dieback on more than 80% of their crown. Poor quality trees represented 1% and 0.3% of the 1988 and 1997 cohorts, respectively.

Only 8 out of the 30 species surveyed from 1988 had more than 50% survivorship: Norway maple (*Acer platanoides* L.), hawthorn (*Crataegus crus-galli* L.), honeylocust (*Gleditsia triacanthos* L.), eastern redcedar (*Juniperus virginiana* L.), Austrian pine (*Pinus nigra* Arnold), Callery pear (*Pyrus calleryana* Decne.), English oak (*Quercus robur* L.), and basswood (*Tilia americana* L.; Figure 6). For the 1997 cohort, only honeylocust (*G. triacanthos*), Kentucky coffeetree (*Gymnocladus dioicus* (L.) K. Koch), and Sargent's crabapple (*Malus sargentii* Rehder) had greater than 50% survivorship out of the 11 species surveyed. None of the surveyed ash trees were still alive in 2018, either because they were killed by Emerald Ash Borer (EAB) or were preemptively removed as the pest outbreak arrived in the region. Only white oak (*Quercus alba* L.) had less than 50% survivorship among species from the 2008 cohort (Figure 6). All other surveyed 2008 species had more than 50% survivorship. Unfortunately, the nature of the original landscaping designs makes it difficult to draw strong inferences about the long-term survival of species such as *Catalpa speciosa* (Warder) Warder ex Engelm., which were planted in smaller quantities and were only observed in one cohort. Additionally, some species such as *Fraxinus* spp. were excluded from the most recent cohort because of issues with pests or perhaps because they have fallen out of favor in the landscaping industry (e.g. susceptibility to emerald ash borer).

Influence of environmental tolerances on survival

Species with low drought tolerance scores in the 1988 cohort were less likely to be alive in 2018 (Figure 7; Table 3 - Model 2). Lower scores from Niinemets and Valladares (2006) suggest a species has less tolerance for a particular environmental condition. For the 1988 cohort, the probability that a tree with low drought tolerance (score of 2) was still alive was 7% (confidence interval (C.I.) = 3-13%) while the probability for a tree with greater tolerance (score of 4.5) was

51% (36-65%). Drought tolerance also had a positive influence on survival in the 2008 cohort though this trend was not statistically significant.

Waterlogging tolerance had a significant positive influence on tree survival in the 2008 cohort (Figure 7; Table 3 - Model 2). A 2008 cohort tree with a waterlogging tolerance score of 1 (low tolerance) had an 88% (C.I. = 76-95%) chance of being alive in 2018 while a tree with a waterlogging tolerance score of 4 had a 97% (C.I. = 93-99%) chance. Interestingly, the 1988 cohort had a negative association with waterlogging tolerance, though this relationship was not significant. Shade tolerance was not a significant predictor of tree survival for either cohort (Figure 7; Table 3 - model 4).

Influence of site factors on survival

According to the 1988 GLMM of site context factors and drought tolerance, both higher drought tolerance and planting locations within traffic islands increased the likelihood of survival (Figure 8; Table 3 - model 5). The other site context factors did not have a significant effect on survival for this cohort. The 1988 site with the lowest predicted probability of survival (2%, C.I. = 0-11%), was 63 m away from and 3.3 m above the highway edge, on a 14º slope primarily facing northeastward, not on a traffic island, on the northbound side, and had a drought score of 1.6. The 1988 site with the highest predicted probability of survival (81%, C.I. = 47-95%) was 125 m away from and 4.9 m above the highway edge, on a 2º slope facing primarily southward, within a traffic island on the southbound side of the highway, and had a drought score of 5. Drought tolerance was the only variable to have a significant effect on the 2008 cohort site context model (Figure 8; Table 3 - model 5).

Change in diversity

Of the surveyed trees, 20 out of 30 species in 1988 (67%) and 6 out of 11 species in 1997 (55%) species, respectively, were still remaining in 2018 (Figure 9). This loss of species decreased the inverse Simpson diversity index for both cohorts in this time period. Although the 1988 cohort lost 10 species since planting, it still had a similar number of species in 2018 as the 2008 cohort which lost no species. Species evenness showed little change for the 1988 and 2008 cohorts between planting and the 2018 survey but had a greater decline for the 1997 cohort. This indicates that the decline in inverse Simpson diversity for 1988 was primarily driven by the loss of species rather than a decline in evenness.

Discussion

Overall Survival

The 1988 cohort's 26% survival 30 years after planting may seem surprisingly low considering the number of trees that were planted. However, after initial losses following planting, urban tree planting percent survival generally declines over time, with the average half-life of a planting population occurring between 10 to 30 years (Hilbert et al. 2019). In their evaluation of urban tree mortality studies, Hilbert et al. (2019) used quartiles of mortality in cohort studies to model three scenarios for predicted tree survivorship: "better-than-normal," "middle-of-the-road," and "worse-than-normal." The 1988 cohort survival results were on par with the low end of the "middle-of-the-road" scenario though as the authors point out, there is a dearth of urban tree planting survival studies beyond two decades to improve the accuracy of their survival scenarios (Figure 10). This study contributes to filling that void. The 30% survival after 21 years for the 1997 cohort falls was classified as "worse-than-normal" but the 2008 cohort's 86% survival after 10 years is much higher than the "better-than-normal" scenario. Blair, et al. (2019) observed a very high survival of highway trees in Florida, U.S. six years after planting (98.5% for 2,711 trees), granted this project had a replacement policy for the first year of planting and installed irrigation at many planting sites. Our study may also underestimate initial mortality since it cannot account for trees which died and were replaced during the planting contract period (usually the first two to three years). Since we lack data about when the 1988 cohort trees died, it is unclear if the 2008 cohort will follow a similar trajectory for the next 20 years.

Direct comparison between the cohorts is complicated by the differences in site characteristics (Figure 2) and site history between the northern and southern portions of I-355 (1988 and 2008 cohorts, respectively). For example, the 1988 cohort trees were more frequently planted on steep slopes and in traffic islands (planting areas between the main highway and smaller roadways). Another difference between the northern and southern portions of I-355 is the age of the road itself and differing construction histories. Notably, road widening has occurred at seven different locations in the northern portion of I-355 since the 1988 cohort was planted (Illinois State Toll Highway Authority 2019). Since its completion, the southern portion of I-355 has not undergone major construction activities. Our review of aerial photography from the past two decades confirmed that construction activities removed approximately 17% of 1988 trees. Yet this approach likely underestimated construction impacts and does not account for stressors generated by construction activities occurring near tree plantings. In Milwaukee, Wisconsin, U.S., street trees were more likely to die if they were located adjacent to construction activities (Koeser et al. 2013). Tree removals and deaths associated with construction highlight the challenge of planting trees in areas with infrastructure replacement cycles that results in the premature death of trees.

Environmental Tolerance Factors and Survival

We focused on drought, waterlogging, and shade tolerance since highway ROW soils can be compacted which can lead to low water and oxygen availability or poor drainage (McGrath and Henry 2016). Additionally, in this study area, trees are typically planted in sunny, open settings which may favor species with low shade tolerance. The higher survival of trees with greater drought tolerance in the 1988 cohort is unsurprising considering the regional climate of northern Illinois, the potential for poor soil quality in the highway ROW, and the role of water stress in tree transplant shock and establishment. Notably, Illinois had extreme droughts (Palmer Drought Severity Index less than -4) in 1988-89 and 2012, in addition to several moderate to severe droughts since 1988 (Illinois State Climatologist 2015). Highway roadside soils can become compacted and lose organic matter during the construction process (McGrath and Henry 2016; Bary, Hummel, and Cogger 2016), and these conditions can limit root growth and consequently water uptake (Day et al. 2010). Water stress is a limiting factor during the establishment phase, a phenomenon referred to as transplant shock (Struve 2009). While irrigation can offset the effects of transplant shock and improve survival (Blair et al. 2019; Roman et al. 2015; Mincey and Vogt 2014), implementing effective irrigation regimes can be difficult in the highway setting (Hirsch and DeJoia 2015). Species with lower water use demand tended to have greater survival rates in the first five years after planting in residential areas in Sacramento, CA, U.S. (Roman, et al. 2014b). The relationship of drought tolerance to survival in this set of highway plantings

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emphasizes the importance of species selection in drier climates and post-construction soils. These results also highlight the utility of the Niinemets and Valladares (2006) rating system for urban trees.

The contrasting effects of waterlogging tolerance on survival in the 1988 and 2008 cohorts likely reflects differences in species composition and planting location as well as local weather conditions. The two species with the greatest waterlogging tolerance in 1988 included *Populus deltoides* Bartr. ex Marsh. and *Salix alba* L.. Both species have fairly low drought tolerance scores (less than 2) and notably were not planted in low lying areas. These species may have fared poorly because they were not close enough to water sources, consequently reducing the survival of trees with high waterlogging tolerance scores. By contrast, in 2008 greater waterlogging tolerance increased the likelihood of survival. Bottomland species which are tolerant of waterlogging are often observed to do well in urban environments where soils can be compacted because of their ability to thrive in soils with low oxygen availability (Day et al. 2000; Watson et al. 2014). The 2008 species with the highest waterlogging tolerance included *Salix alba* L., *Alnus glutinosa* (L.) Gaertn., *Acer saccharinum* (L.), and *Acer* x *freemanii* Murray. Both *S. alba* and *A. glutinosa* in 2008 were both planted closer to stormwater systems and with the exception of *S. alba* these species also are moderately drought tolerant. Additionally, 2008 to 2011 were unusually wet years for Illinois and may have also contributed to favoring the survival of waterlogging tolerant species in the 2008 cohort.

Climate models predict that in the future, Illinois temperatures could increase by 2.2 to 7.8 ^{o}C, which could exacerbate short term droughts (Wuebbles et al. 2021). Though for the past 120 years precipitation has increased in Illinois and models predict that increase will continue though most of this extra precipitation will occur in the winter and spring (Wuebbles et al. 2021). These predictions may indicate waterlogging tolerance could become a more important species trait in the future. These observations highlight the challenge of finding species which are tolerant to the multiple and often contrasting stressors that can be encountered in the highway environment and in the face of changing climates.

Highway Context Factors and Survival

While many highway roadside soil properties improve with increasing distance from the highway edge, distance to highway was not an important variable in our models. Generally, when further away from the highway edge, macronutrients increase (Akbar et al. 2012) while heavy metals (Chen et al. 2010; Werkenthin et al. 2014), polyaromatic hydrocarbons (Sídlová et al. 2009), pH and clay content (Trammell et al., 2011) and de-icing salt (Fay and Shi 2012) decrease. Other research has observed that plant cover (Rentch et al. 2005), shade tree crown condition (Blair et al. 2019), tree growth (Heintzman, Titus, and Zhu 2015), and flower bud damage (Berkheimer et al. 2006) can vary with changing distance from the highway. Trammell and Carreiro (2011) did not observe distance effects on plant community composition. While soil properties can also be less favorable to plant growth downhill from roadsides (Zhao et al. 2007; Trammell et al. 2011), elevation relative to the highway was not an important variable in our model. The distance de-icing salts can affect trees beyond the pavement can vary with many factors, though deposition appears to be greatest within approximately 10 m of the road edge and effects can be observed up to 100 m away (Blomqvist and Swedish National Road a...). Since a clear zone of about 9 m is maintained on I-355 to keep trees away from the highway edge, it is possible that the study trees do not experience the most extreme impacts of highway conditions on soil immediately adjacent to the roadside.

Highway slopes also have a reputation for being difficult places to even establish herbaceous vegetation (Curtis and Claassen 2007; Ament, et al. 2011; Hopkinson, et al. 2016), though it was not an important factor in the site context models. Roadside cut-slopes and embankments tend to have high rates of runoff and poor soil quality with low organic matter, high pH, high electrical conductivity, and high bulk density (Claassen and Zasoski 1998; Trammell et al 2011; Bakr et al. 2015). Blair et al. (2019) observed that small statured trees on steeper slopes tended to have poorer crown quality, though they speculated that the usage of small berms to prevent irrigation from running downslope before it can infiltrate the root zone could help mitigate low water availability. Interestingly, while many of the 1988 traffic island planting sites were on sloped ground, these trees were more likely to be alive. One potential explanation for this observation is that since these traffic islands are located at interchanges with local roads there may have been more incentive to maintain tree plantings at these higher visibility sites.

Slope aspect can influence microclimate and soil temperature which then influence plant growth (Forman et al. 2002; Arenas et al. 2015). Hopkinson et al. (2016) observed greater herbaceous cover vegetation on east facing slopes, though the sample size for this group was smaller compared to slopes facing other directions. In the I-355 study sites, about 36% of west facing slopes faced towards the highway while the rest faced away or were on flat ground. Considering the prevailing westerly wind direction in the region, it was expected that west facing slopes would have lower survival because they receive wind blown off the highway and tend to have higher soil temperatures. East facing slopes tended to have lower survival (though not statistically significant), however. The results of the site context analysis suggest that other factors play a more important role in long-term tree survival for these planting cohorts.

Changes in Diversity

Higher mortality for some species such as *Malus* spp., *P. deltoides*, *Populus tremuloides* Michx., and *Robinia pseudoacacia* L. in 1988 and 1997 led to a decrease in planted tree diversity of these two cohorts between the time of the initial as-built records to 2018, potentially because of differences in site conditions, species tolerances, and pest outbreaks. The Emerald Ash Borer (*Agrilus planipennis*) outbreak explains the loss of the two *Fraxinus* species planted on I-355, both of which accounted for approximately 31% of the 1997 cohort. Since each planting site only contained one species, adverse conditions at a particular location could have led to substantial losses for a particular species and consequently diversity and richness. It is also notable that the 1988 cohort had a greater frequency of trees with low drought tolerance scores (Figure 7). Since low drought tolerance species had a lower likelihood of survival, the loss of species intolerant of conditions in this setting also likely contributed to the loss of species and decline in diversity. This observation lends support to the hypothesis that because of stressful conditions there may be limits to the number of tree species some urban environments can support (Sjöman et al. 2016). Additionally, species such as *Cercis canadensis* L., *Populus* spp., and *Robinia psuedoacacia* L. have comparatively shorter lifespans (NRCS USDA 2020) which may have also contributed to their low survival in the 30-year-old cohort. Variability in survival between species has been observed in many tree planting studies (Miller and Miller 1991; Struve et al. 1995; Nowak et al. 2004; Thompson et al. 2004; Lu et al. 2010), and is an important reminder that planting high diversity does not guarantee the long term diversity of tree planting programs.

Study Limitations

One key limitation of this study is the lack of documentation about when and why the majority of trees in the study died or were removed. Nevertheless, this dataset can offer useful insights into tree survival in highway ROWs in continental climates. The patterns we observed regarding species' environmental tolerances and the influence of site context variables are consistent with expectations and other research on stressful growing conditions in the highway ROW. Granted, interpretation and extrapolation of the results are limited by the opportunistic nature of this observational study; not every species could be observed across the entire gradient of highway landscape characteristics. Using planting site as a random effect in the statistical models was intended to help address this shortcoming. Additionally, modeling some predictors (e.g. environmental tolerances) as separate models may have contributed to the over- or under-prediction of some associations but was necessary to avoid co-varying predictors. This study does rely on the accuracy of as-built drawing records not produced by the research team. However, considering that these records were used to verify terms of a contract we feel reasonably confident in their accuracy. Since we did not have cultivar specific environmental tolerance data, we relied on species level data though cultivars can differ in their environmental tolerances (Hirons et al. 2021). Considering the widespread usage of tree cultivars in the landscaping industry (Lohr 2013; Thompson et al. 2021), further documentation of cultivar specific environmental tolerances is needed. And since we could only collect data from planting sites that were safely accessible, our results are most applicable to highway ROWs with slopes less than 20 degrees.

Conclusion

In re-inventorying three cohorts of highway plantings (10, 21, and 30 years old), survival was fairly low in the 1988 and 1997 planting cohorts (26 and 31%, respectively), though these percentages are in line with modeled predictions for 21 to 30 year old plantings (Hilbert et al. 2019). Survivorship was substantially higher for the 2008 cohort, 86%. In the 1988 cohorts, drought tolerant trees were more likely to still be alive in the 2018 survival survey. Site context variables such as the distance from the highway edge or slope were not significant predictors of tree survival. Though in the 1988 cohort, trees planted in areas between the highway and smaller roads (traffic islands) were more likely to be alive. Variability in species survival for the 1988 and 1997 plantings led to lower tree diversity in 2018 compared to diversity at the time of the as-built planting records for these two cohorts. As of 2018 both species richness and inverse Simpson diversity were still greater in the 1988 cohort compared to the 2008 cohort, however. The results of this study highlight the importance of species and planting site selection on long-term tree survival. It also illustrates the challenges of maintaining long-term tree diversity in challenging planting sites.

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Figures

Figure 1: Map of the study area in the Chicago metropolitan region of Illinois, U.S. showing the location of planting sites from the 1988 (diamonds), 1997 (triangles), and 2008 (squares) cohorts.

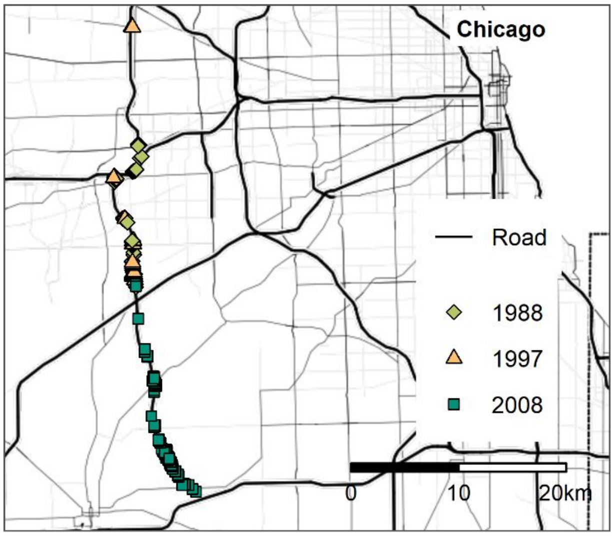

Figure 2: Density kernel estimates and frequency plots of site characteristics for 1988 and 2008 planting sites evaluated in the re-inventory: distance of planting site center to highway , elevation relative to highway), slope, slope aspect easting component, slope aspect northing component, location within or outside of traffic islands, and location on the northbound or southbound side of the highway. Gray bar in the distance panel indicates the average clear zone width maintained on I-355 (approx. 9 m).

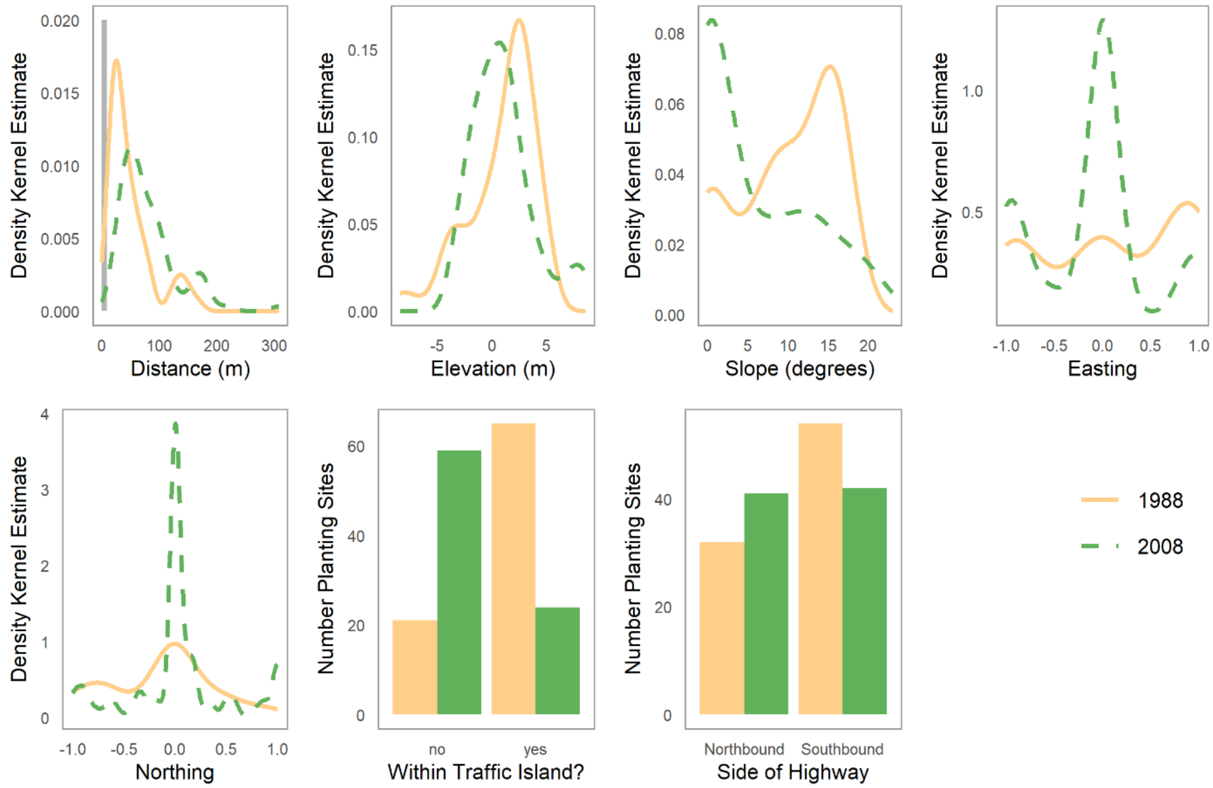

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Figure 3: Diagram outlining the process of site selection and site factors used to evaluate tree survival on I-355.

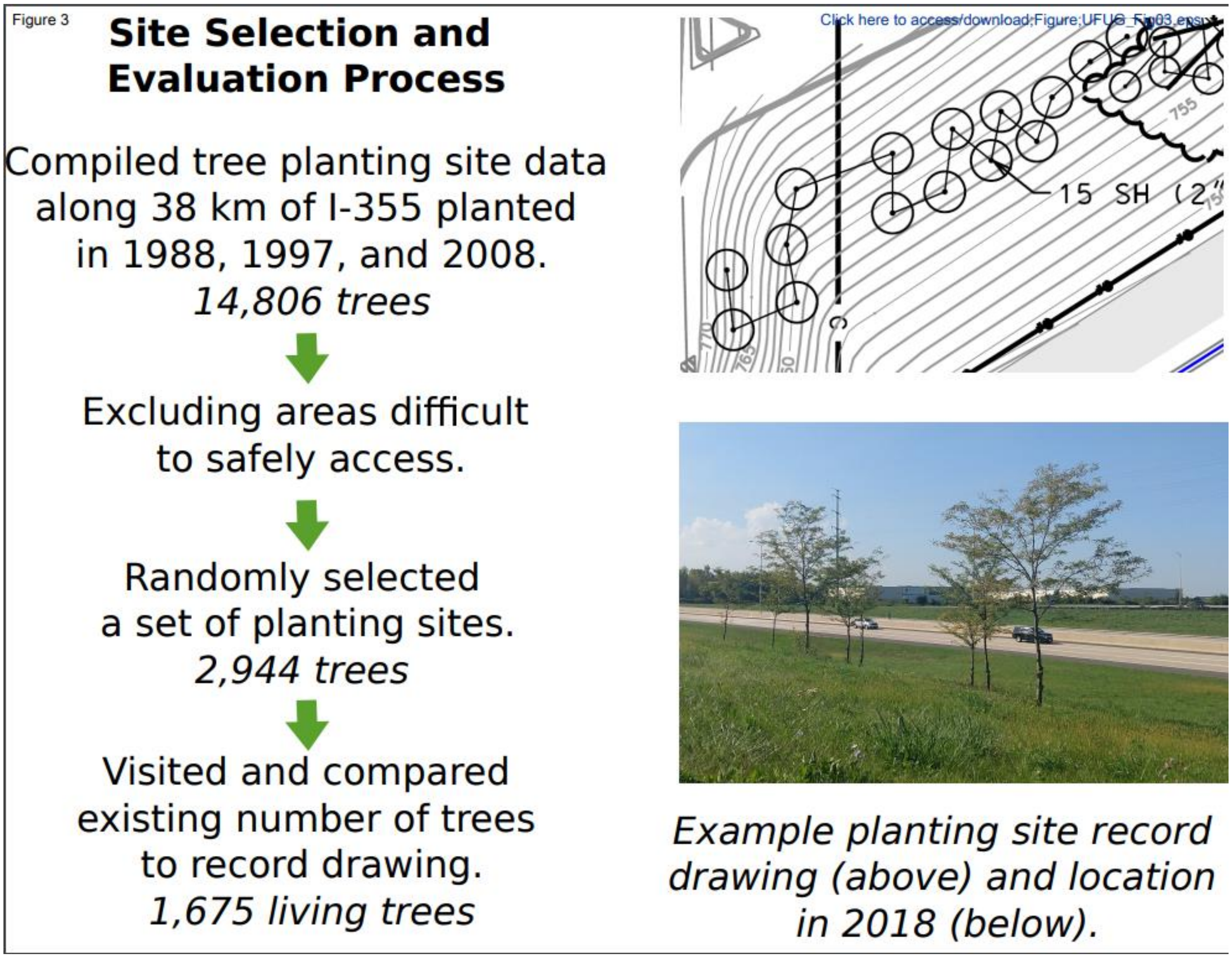

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Figure 4: Site factors used to evaluate tree survival on highway I-355. Note this photograph shows an example of a traffic island, defined in this study as a planting site located between the highway and an entrance or exit ramp.

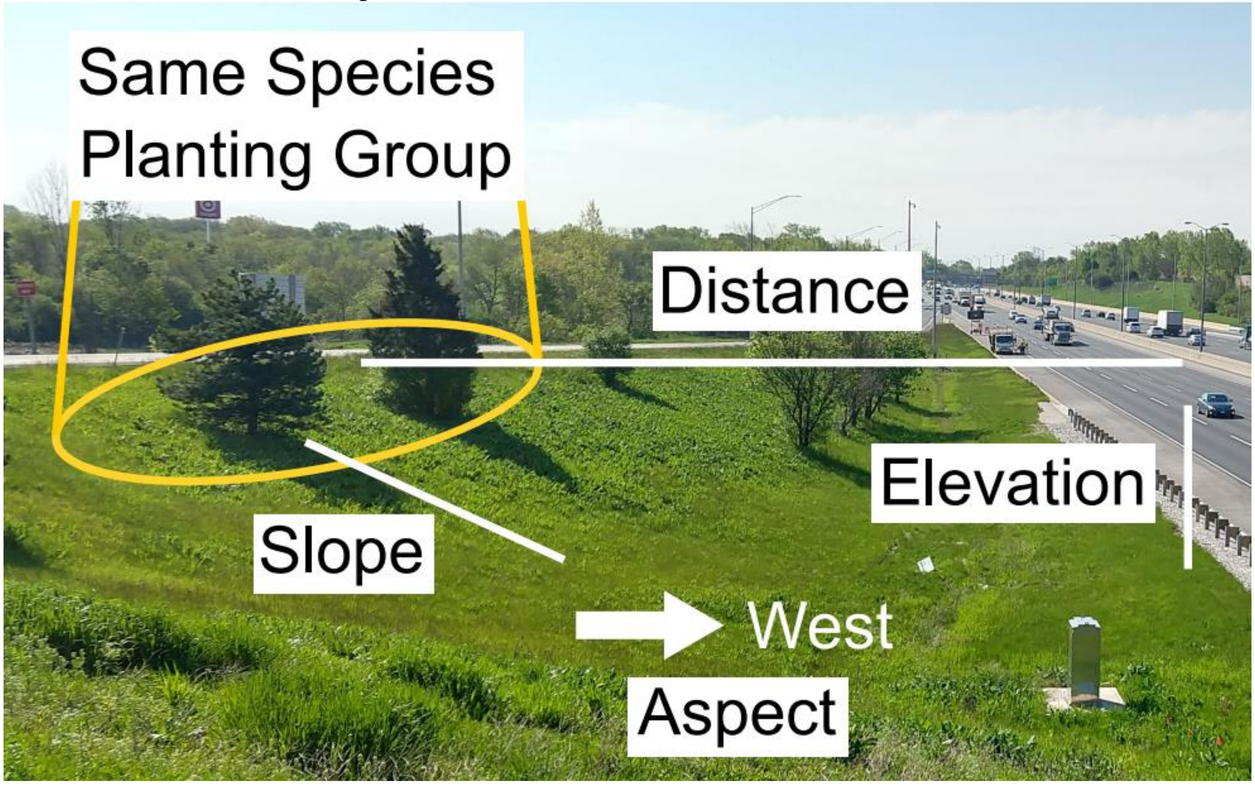

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Figure 5: GLMM predictions of the probability of survival of I-355 trees for each planting cohort. Error bars represent approximate 95% confidence intervals

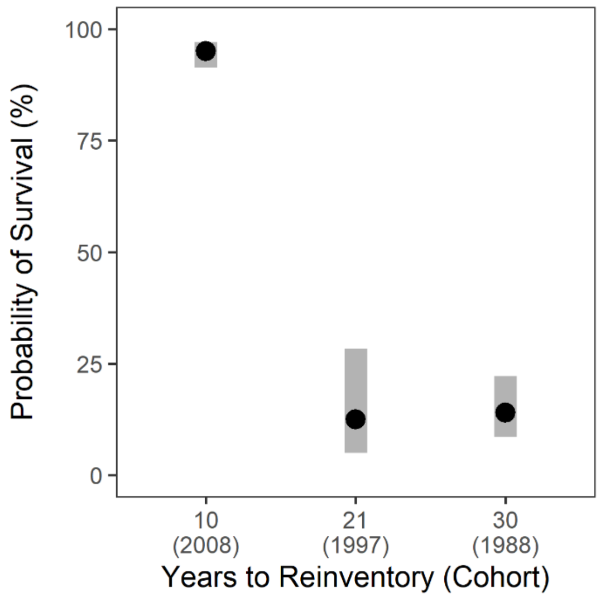

Figure 6: The percentage (bars) and quantities (fractions) of surveyed trees found alive and dead, grouped by species and planting cohort year. Fractions indicated the ratio of living trees (numerator) to the total quantity of surveyed trees (denominator). Species without percentage bars were not planted in a given cohort.

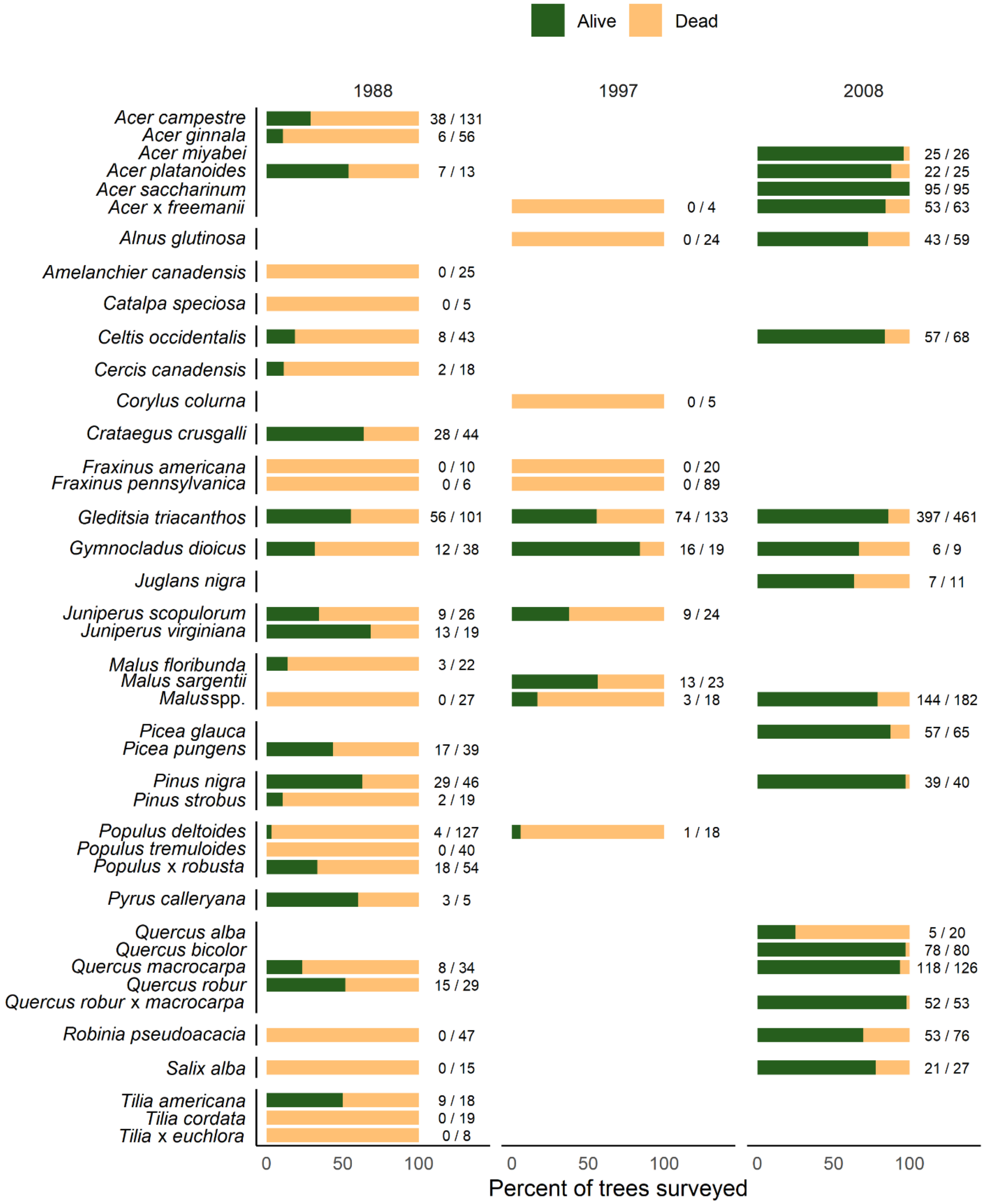

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*Figure 7: The distribution of percent survival of each planting site arranged by drought, shade, and waterlogging tolerances. Lines indicate predicted probability of survival at time of reinventory based on GLMM models with approximate 95% confidence intervals. Scores were assigned based on classification by Niinemets and Valladares (2006); a low score indicates low tolerance for a given condition. Stars indicate a significant GLMM: *** indicates p < 0.001, * indicates p < 0.05.*

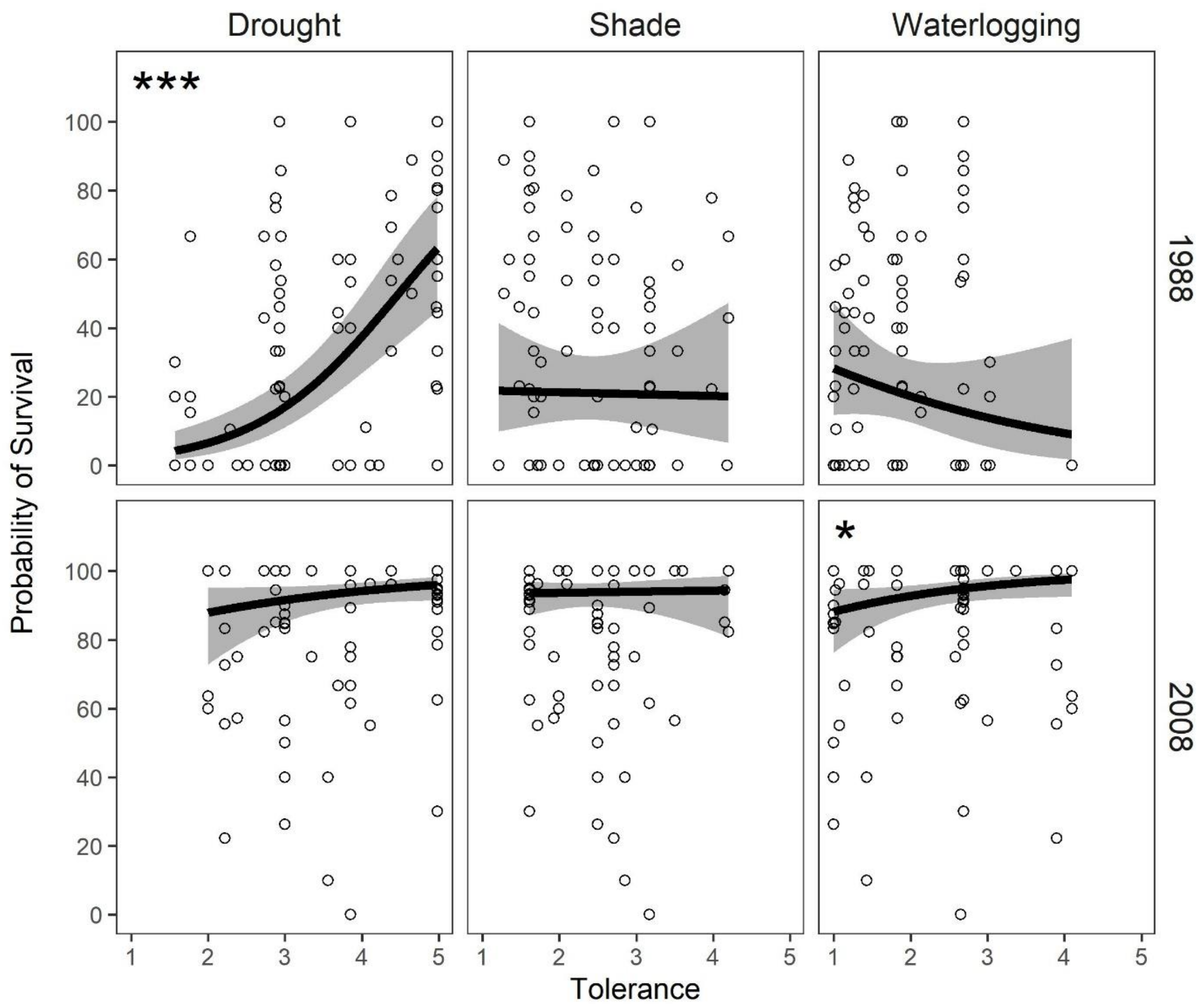

Figure 8: Log odds for model variables predicting the likelihood of survival for the 1988 and 2008 cohorts. Black circles indicate a variable's log odds were significantly different from 0 (alpha = 0.05). Error bars represent approximate 95% confidence intervals.

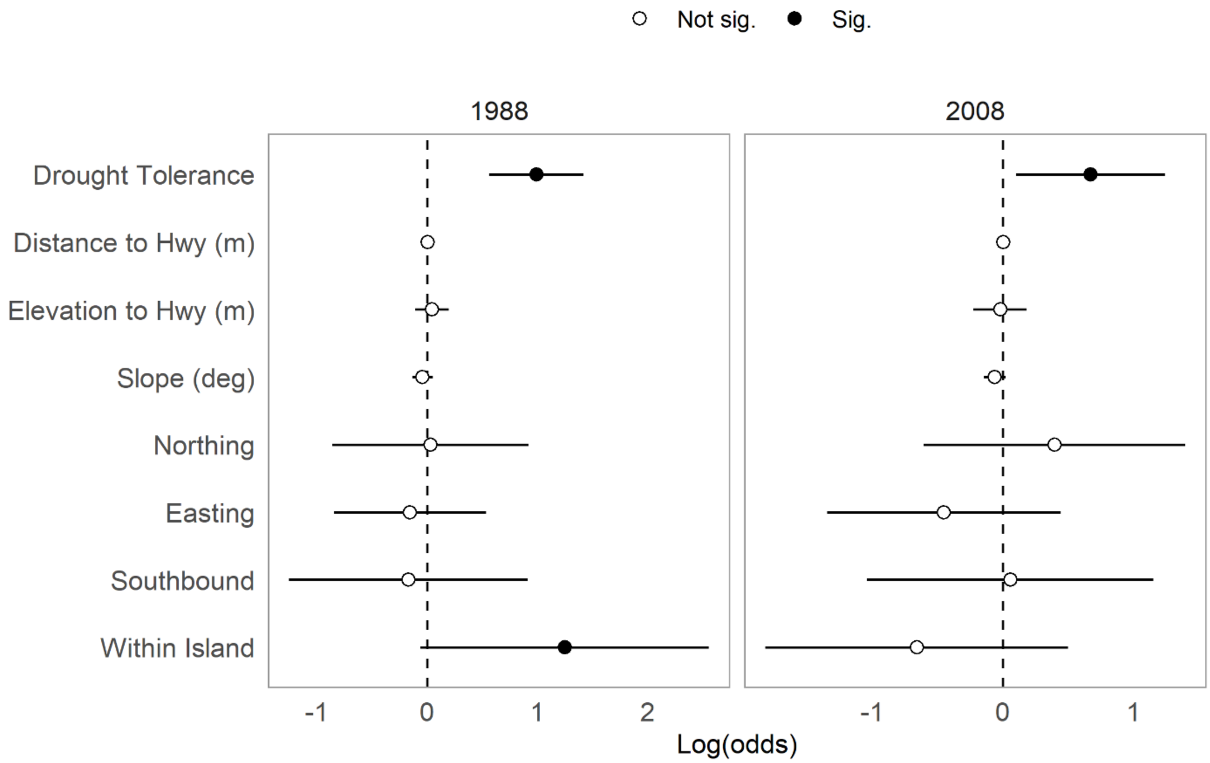

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Figure 9: Comparison of the total number of species (a), inverse Simpson diversity index (b), and evenness (c) of the survival survey trees at the time of planting ("Orig.") and in 2018 ("Obs. 2018"). Note: cultivars were grouped by species for this analysis.

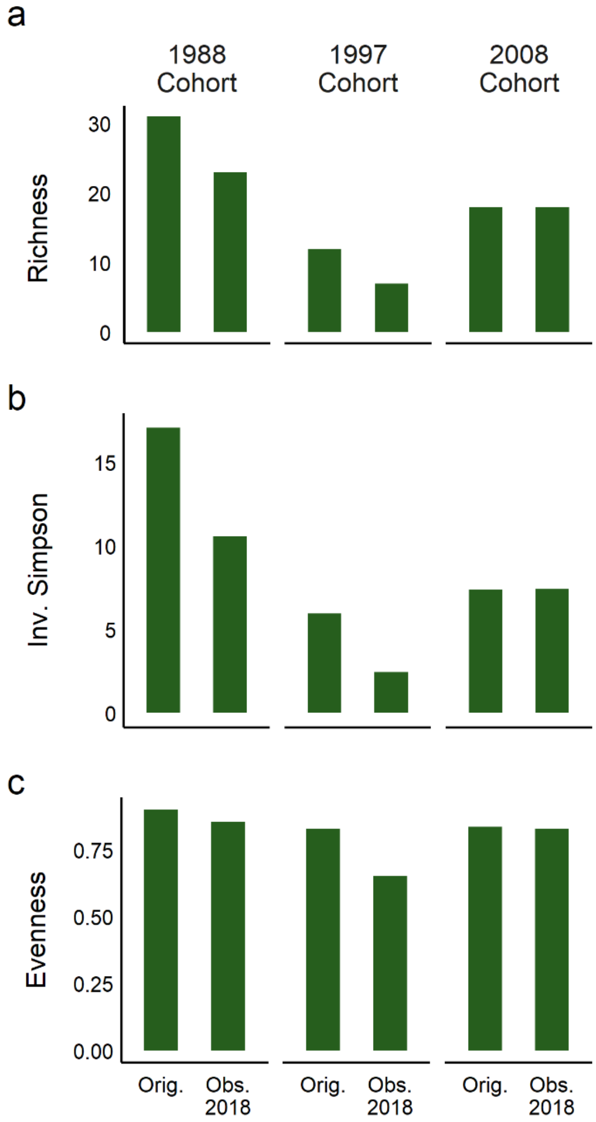

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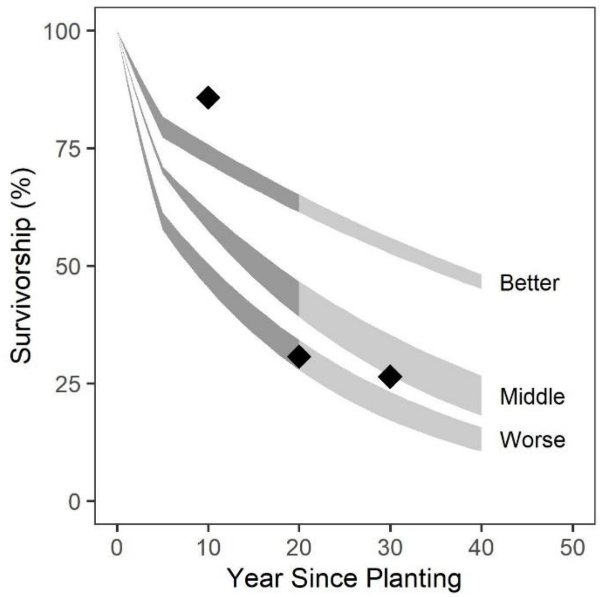
Figure 10: Comparison of I-355 cohort survival with better, middle, and worse case estimated urban tree survival based on analyses by Hilbert, et al. (2019). Diamonds indicate percent survivorship of I-355 trees. Estimates of survival after 20 years are based on a smaller sample size and are consequently extrapolations, indicated by the lighter gray color



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Tables

Table 1: Planting site variables evaluated in the study and the median, minimum, and maximum values across all planting sites. Drought, shade, and waterlogging tolerance scores are from Niinemets and Valladares (2006).

Variable	Description	Median	Minimum	Maximum
Survival	The percentage of a planting site's trees that are alive.	60	0	100
Distance (m)	Distance from the edge of highway pavement to the center of the planting site.	53.1	10.2	307.6
Drought Tolerance	Rating of the ability of a species to tolerate drought conditions. A higher number indicates greater tolerance.	3.6	1.6	5.0
Easting	The east-west component of slope aspect (the compass direction a slope faces as observed when looking downslope). -1 indicates west facing, 1 indicates east facing.	0	-1	1
Elevation (m)	Elevation of the planting site relative to the edge of the highway pavement.	0.9	-8.4	8.6
Highway side	A binary variable indicating if a planting site was on the southbound or northbound side of the highway.	-	-	-
Northing	The north-south component of slope aspect (the compass direction a slope faces as observed when looking downslope). -1 indicates south facing, 1 indicates north facing.	0	-1	1

Shade Tolerance	Rating of the ability of a species to tolerate shade conditions. A higher number indicates greater tolerance.	3	1	4
Slope (deg)	The slope of the planting site.	7	0	23
Traffic Island	A binary variable indicating if a planting site is located within a traffic island — the unpaved area between the highway and an entrance or exit ramp.	-	-	-
Waterlogging Tolerance	Rating of the ability of a species to tolerate waterlogged conditions. A higher number indicates greater tolerance.	2.13	1	4.1

Table 2: Quantity of trees planted along the study highway (Interstate 355, Illinois, United States) in 1988, 1997, and 2008 based on as-built planting records provided by the landscape contractors. This is contrasted with the quantity of trees re-inventoried across 224 locations in 2018, and the quantity of trees found alive during the 2018 re-inventory.

Year	**Total Quantity Planted**	**Survival Study Subset (Percent of Total)**	**Surveyed Alive (Percent of Subset)**
1988	8,466	1,084 (13%)	287 (26%)
1997	848	377 (44%)	116 (31%)
2008	5,492	1,483 (27%)	1,272 (86%)
Total	14,806	2,944 (20%)	1,675 (57%)

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Table 3: Generalized linear mixed model results predicting the effects of cohort, environmental tolerances, and site context on tree survival at a given planting site. ICC Cond. = conditional intraclass correlation coefficient (accounts for both fixed effects and random effects variation). AUC = area under curve of a receiver operating characteristic curve. R^2 Cond. = conditional coefficient of determination. 1|Planting Site indicates that planting site was used as a random effect in the model.

Model	Formula	Year	χ^2 p-value	ICC Cond.	AUC	R^2 Cond.
1	Survival (%) ~ Cohort + (1|Planting Site)	All	<0.001	0.37	0.94	0.77
2	Survival (%) ~ Drought Tolerance + (1|Planting Site)	1988	<0.001	0.37	0.88	0.57
		2008	0.92	0.59	0.89	0.59
3	Survival (%) ~ Shade Tolerance + (1|Planting Site)	1988	0.24	0.58	0.89	0.59
		2008	0.12	0.47	0.89	0.49
4	Survival (%) ~ Waterlogging Tolerance + (1|Planting Site)	1988	0.87	0.51	0.89	0.51
		2008	0.05	0.47	0.89	0.51

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5	Survival (%) ~ Distance + Elevation + Slope + Northing + Easting + Traffic Island + Highway Site + Drought Tolerance + (1|Planting Site)	1988	<0.001	0.34	0.88	0.58
		2008	0.45	0.42	0.89	0.5