URBAN FORESTRY & URBAN GREENING

Tree mortality rates and tree population projections in Baltimore, Maryland, USA

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Abstract: Based on re-measurements (1999 and 2001) of randomly-distributed permanent plots within the city boundaries of Baltimore, Maryland, trees are estimated to have an annual mortality rate of 6.6% with an overall annual net change in the number of live trees of –4.2%. Tree mortality rates were significantly different based on tree size, condition, species, and land use. *Morus alba, Ailanthus altissima,* and trees in small diameter classes, poor condition, or in transportation or commercial – industrial land uses exhibited relatively high mortality rates. Trees in medium- to low-density residential areas exhibited low mortality rates. The high mortality rate for *A. altissima* is an artifact of this species distribution among land use types (24% were in the transportation land use). Based on a new tree population projection model that incorporates Baltimore's existing tree population and annual mortality estimates, along with estimates of annual tree growth, Baltimore's urban forest is projected to decline in both number of trees and canopy area over the next century. Factors affecting urban tree mortality are discussed.

Key words: growth projection, land use, urban forest change, urban forestry

Introduction

Urban tree mortality is a significant factor affecting urban landscape change, yet little is known about the rates of urban tree mortality or the various factors that affect mortality rates. To help managers to minimize urban tree mortality, factors that affect mortality must be understood. In addition, to project urban tree population effects into the future, mortality and natality rates must be known.

Most of the limited research to date on urban tree mortality has focused on street tree populations. In a study of street tree mortality between 1978 and 1985 in Syracuse, New York (NY), mortality rates were found to differ by tree size and condition (Nowak 1986). Trees larger than 77 cm in diameter at breast height (1.37 m) (dbh) exhibited a significantly high mortality rate (5.4% average annual mortality rate), as did trees with crown deterioration (6.4% average annual mortality rate). Trees that were considered to be stable and healthy exhibited a significantly low mortality rate (1.4% average annual mortality rate).

Many street tree mortality studies have focused on newly planted tree mortality rates. A study in Boston revealed that annual street tree mortality over a 10-year period averaged 9%, with mortality rates of newly planted trees varying from 3% to greater than 38% depending upon tree planting contractors (Foster & Blaine 1978).

Annual mortality of newly planted trees in the Oakland, California area averaged 19% over a two-year pe-

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1618-8667/04/02/03-139 $ 30.00/0

riod. Areas of lower socio-economic status exhibited the highest tree mortality with percent mortality most strongly correlated with percent unemployment. Trees with adjacent land uses of apartments and public greenspaces had significantly high mortality, while trees next to single family residences or rapid transit stations exhibited low mortality (Nowak et al. 1990).

In another study in Oakland, tree survival rates of inner-city street trees between 1978–1984 were approximately 60–70% (5.8–8.2% annual mortality rate) for trees planted with community participation versus less than 1% survival (>50% annual mortality rate) for trees planted without community participation (Sklar & Ames 1985). Common causes for newly planted tree mortality in Northern England were water and nutrient stress (56%), vandalism (18%), tree guard girdling (12%), soil compaction (9%), and improper staking and tying techniques (5%) (Gilbertson & Bradshaw 1985).

While there has been some research on street tree mortality, there has been no research on tree mortality across the urban landscape. To help understand differences in urban tree mortality, permanent plots were established in all land uses in Baltimore, Maryland (MD), in 1999 and then these plots were re-measured in 2001. The objective of this study was to determine what annual average mortality rates were across the city, and if these rates differed by land-use type, tree size, tree species, or initial tree condition.

Study area and methods

In the summer of 1999, 202 field plots (0.04 ha/plot) were randomly sampled among eight different land-use types (i.e., stratified random sampling) in Baltimore, MD:

- High-density residential (50 plots): attached single unit row housing, garden apartments, high-rise apartments/condominiums, mobile home and trailer parks. Areas of more than 90 percent high-density residential units with more than 19.8 dwelling units per hectare.
- Low to medium-density residential (45 plots): detached single-family/duplex, attached single-unit row housing, yards, and associated areas. Areas of more than 90 percent single-family/duplex units and attached single-unit row housing, with lot sizes of less than two hectares but at least 0.05 ha (0.5–19.8 dwelling units per ha).
- Forests (42 plots): forested areas including brush areas that do not produce timber or other wood products, but may include cut-over timber stands, abandoned agriculture fields, or pasture. These brush areas have such vegetation as sumac, vines, roses, and tree seedlings.
- Commercial/industrial (25 plots): retail and wholesale services areas; manufacturing and industrial parks, including associated yards, parking areas, warehouses, and research laboratories.
- Barren (10 plots): beaches, bare exposed rock, and bare ground (wetland areas included).
- Institutional (10 plots): elementary and secondary schools, middle schools, junior and senior high schools, public and private colleges and universities, military installations (built-up areas only), churches, medical and health facilities, correctional facilities, and government offices and facilities that are clearly separable from surrounding land cover.
- Transportation (10 plots): major transportation routes, highways and railways, and airports and water ports.
- Urban open (10 plots): urban areas whose use does not require structures, or urban areas where non-conforming uses characterized by open land have become isolated. Included are golf courses, parks, recreation areas (except areas associated with schools or other institutions), cemeteries, and entrapped agriculture and undeveloped land within urban areas.

On each plot, all trees were recorded with measurements including: actual land use, tree species, dbh (for multi-stem trees: quadratic mean of dbh was used), and tree condition based on percent of branch dieback in crown: excellent (<1%); good (1–10%); fair (11–25%); poor (26–50%); critical (51–75%); dying (76–99%), and dead (100%).

In the summer of 2001, a re-inventory of plots in Baltimore, MD was conducted to estimate changes in urban forest structure. Two plots could not be re-accessed for measurement, thus results are based on a sample of 200 plots. All plot information and tree characteristics used in the 1999 inventory were updated by the second measurement. In addition, new trees (> 2.5 cm dbh) that were planted or are the result of natural in-growth were measured. Trees that were removed or missing were noted. Each sampled tree (n = 1,396) was categorized into one of seven life-status groups according to the change in its condition between 1999 and 2001 (Table 1).

To estimate total population parameters and changes in the population totals between 1999 and 2001, the Urban Forest Effects (UFORE) model was used (Nowak & Crane 2000; Nowak et al. 2002).

Average annual mortality rates were calculated by land-use type, dbh class, species, and condition class based on:

$$\text{Average annual mortality rate} = 1 - x$$

Where x = average annual survival rate: $\sqrt{N_1/N_0}$, N_0 = total living trees in 1999, and N_1 = number of trees living in 2001 that were recorded in 1999.

Chi-square tests were used to test for significant differences in mortality among land-use types, dbh classes, tree species, and tree condition classes. The level for statistical significance was set at alpha = 0.05 for the overall test. In testing for differences between individual classes, the alpha level was lowered to either 0.025 or 0.005 due to the multiple number of comparisons.

To project future tree population totals, canopy area change, and average tree life span given varying mortality rates, a population projection model was developed. This new model uses annual time steps over a 100-year period to project tree population totals in 2.5 cm dbh classes. It also projects relative change in canopy area (% change from base year) using canopy width formulas for sugar maple shade trees that were based on dbh (Frelich 1992). Sugar maple was chosen as a representative species for canopy growth as its formula produced the median value of relative canopy growth among 12 possible species.

Inputs to the model are the number of trees in 2.5 cm dbh classes (last dbh class is >76.2 cm) in the population at year 0; number of new 2.5 cm dbh trees established annually; and average annual mortality and growth rates for 0–7.6, 7.7–15.2, 15.3–30.5, 30.6–45.7, 45.8–61.0, 61.1–76.2, and >76.2 cm dbh classes. Within the model, number of trees in each dbh class change annually based on ingrowth (including planting estimates) and mortality.

Mortality rates used varied based on results from the field data. Due to the relative short period to quantify tree growth in Baltimore (2 years), average annual dbh growth rates were estimated based on an annual growth rate of 0.38 cm/year for trees in forests and transportation land use (closed-canopy structure); 0.83 cm/year for trees on residential, commercial/industrial, and barren land uses (open structure); and 0.61 cm/year for institutional and urban open land uses (mixed structure), based on measured data from trees in a similar climate zone (Nowak 1994). The model outputs annual estimates (from year 1–100) of number of trees in each dbh class and percent change in canopy area from year 0.

Projected average dbh growth rate for the tree population was 0.63 cm/year based on Baltimore's tree distribution among land uses. To test the sensitivity of tree population projections to dbh growth a bound of 0.125 cm was applied (0.51–0.76 cm/year growth bound). To calculate average life span, the number of trees dying each year was projected. Life span (years) was weighted by its associated number of trees to calculate the average tree life span. To test the sensitivity of the model to mortality rates, mortality rate in each dbh class was increased or decreased by 1% and 5%. In decreasing mortality, a minimum mortality rate of 0.1% was set for each dbh class to avoid a negative or 0% mortality rate.

Table 1. Estimated total tree population (200 plots) in Baltimore in 1999 and 2001 based on analyses using the Urban Forest Effects (UFORE) model (Nowak & Crane 2000). Standard error is given in parentheses

1999		2001		SE	% 1999 total
Status	Population	Status	Population		
Live	2,535,600	Live	2,210,200	(470,300)	80.7
		Dead	131,400	(60,700)	4.8
		Removed	194,000	(51,200)	7.1
					92.6
Dead	201,600	Dead	167,500	(50,600)	6.1
		Removed	34,100	(13,400)	1.2
					7.4
Non-existent	0	Live	115,600[a]	(25,200)	
		Dead	2,300[b]	(2,300)	
Total trees	2,737,200		2,627,000[c]	(570,500)	100

[a]5.5 trees/ha
[b]0.1 trees/ha
[c]total excluding removed trees

Results

The overall average annual mortality rate for the trees in Baltimore was 6.6%. Of the approximately 2.5 million live trees that existed in 1999, about 2.2 million were left in 2001; a loss of about 325,000 trees (Table 1). Of those 325,000 trees, about 60% were removed; the other 40% were standing dead trees. Besides the loss of trees, approximately 116,000 new trees were established (5.5 trees/ha) between 1999 and 2001. The overall net change in live trees was an annual loss of 4.2%.

Of the approximately 202,000 dead standing trees in 1999, 17% were removed by 2001 (Table 1). The overall tree population (live and dead standing trees) changed from about 2.7 million in 1999 to 2.6 million in 2001, a loss of 110,000 trees (4%).

Table 2. Percent average annual mortality by land-use type in Baltimore between 1999–2001

Land-use type	Percent Mortality	N	Sign.*
Transportation	20.2	33	abcd
Commercial/Industrial	10.6	15	e
Urban Open	8.2	228	af
High Density Residential	6.0	77	b
Forest	5.9	728	cg
Low-Medium Density Residential	2.2	136	defg
Institutional	0.0	4	
Barren	0.0	7	

*Land-use types with the same letter indicate statistically significant difference at α = 0.025.
N = total sample size

Table 3. Percent average annual mortality by dbh class in Baltimore between 1999–2001

DBH (cm)	Percent Mortality	N	Sign.*
0–7.6	9.0	528	ab
7.7–15.2	6.4	267	c
15.3–30.5	4.3	201	ad
30.6–45.7	0.5	109	bcd
45.8–61.0	3.3	62	
61.1–76.2	1.8	28	
>76.2	3.1	33	

*dbh classes with the same letter indicate statistically significant difference in measurement at α = 0.025.
N = total sample size

Mortality rates differed by land-use type, dbh class, species, and condition class. Trees in transportation land uses had a significantly higher annual mortality (20.2%) than most other land uses (Table 2). Trees on

Table 4. Percent average annual mortality (1999–2001) by species with a minimum sample size (N) of 10

Species	Percent Mortality	N	Sign.*
Morus alba L.	18.9	35	abcdefghi
Ailanthus altissima (P. Mill.) Swingle	17.6	78	jklmnopqr
Cornus florida L.	13.2	61	stuv
Acer negundo L.	12.6	34	wx
Acer saccharinum L.	9.0	29	
Robinia pseudoacacia L.	7.4	49	
Ulmus parvifolia Jacq.	7.1	22	
Fraxinus americana L./ F. pennsylvanica Marsh.	6.8	107	aj
Sassafras albidum (Nutt.) Nees	6.5	16	
Quercus phellos L.	6.2	25	
Acer platanoides L.	6.1	17	
Ulmus rubra Muhl.	4.3	71	bk
Liriodendron tulipifera L.	3.8	40	cl
Quercus rubra L.	3.6	57	dm
Prunus serotina Ehrh.	3.3	78	ens
Picea abies (L.) Karst.	3.2	16	
Fagus grandifolia Ehrh.	2.3	134	fotw
Acer rubrum L.	1.3	39	gpu
Quercus alba L.	1.0	51	hqvx
Carya tomentosa (Lam. ex Poir.) Nutt.	0.0	19	ir
Pinus strobus L.	0.0	17	
Cornus alternifolia L. f.	0.0	16	
Nyssa sylvatica Marsh.	0.0	16	
Carpinus caroliniana Walt.	0.0	12	

*Conditions with the same letter indicate statistically significant difference in measurement at α = 0.005.
N = total sample size

Table 5. Percent average annual mortality (1999–2001) by 1999 tree condition

Condition	Percent Mortality	N	Sign.*
Dying	22.5	35	abcd
Critical	14.7	33	ef
Poor	7.7	108	a
Fair	5.6	332	be
Good	4.2	560	cfg
Excellent	9.2	160	dg

*Conditions with the same letter indicate statistically significant difference in measurement at α = 0.025.
N = total sample size

medium- to low-density residential areas had a significantly lower annual mortality rate (2.2%) than most other land uses.

Small trees (0–7.6 cm dbh) had a significantly higher annual mortality rate (9.0%) than trees with 15.3–45.7 cm dbh (Table 3). Trees in the 7.7–15.2 cm (6.4% annual mortality) and 15.3–30.5 cm (4.3% mortality) dbh classes also had significantly higher mortality than trees with 30.6–45.7 cm dbh (0.5% mortality).

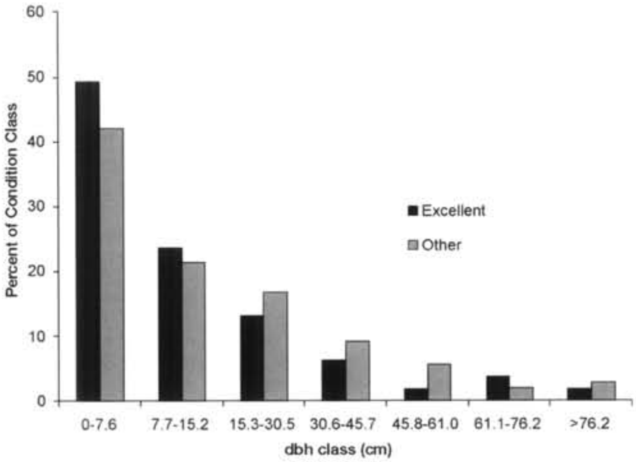

Fig. 1. Percent of "excellent" and "other" condition trees by dbh class.

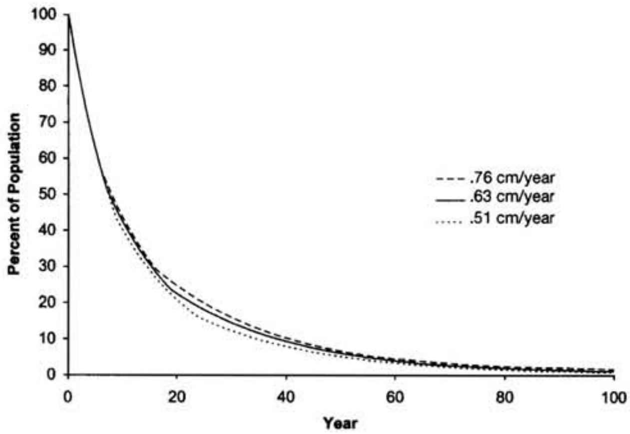

Fig. 2. Percent of tree population remaining after tree planting with a variable annual average mortality rate based on Table 3, and varying annual dbh growth rates. Average dbh growth rate for Baltimore is estimated to be 0.63 cm/year. At 0.63 cm/year: average life span for a tree is 15 years and 30% of the population remains at this age. At 0.76 cm/year: average life span for a tree is 16 years and 29% of the population remains at this age. At 0.51 cm/year: average life span for a tree is 14 years and 31% of the population remains at this age.

In terms of species differences, *Morus alba* (18.9% annual mortality) and *Ailanthus altissima* (17.6%) exhibited significantly higher mortality rates than several other species (Table 4). *Cornus florida* (13.2%) and *Acer negundo* (12.6%) also had a significantly higher mortality rate than a few other species. These four species did not exhibit any significant differences in dbh distribution, but *A. altissima* did have 24.4% of its trees in the transportation land use and comprised 58% of the transportation land-use sample. A significant difference in *A. altissima* mortality was found among land-use types (alpha = 0.05) with mortality significantly higher on transportation land uses (35.1% annual mortality) than on high-density residential (3.6%) and low-medium density residential lands (0.0%).

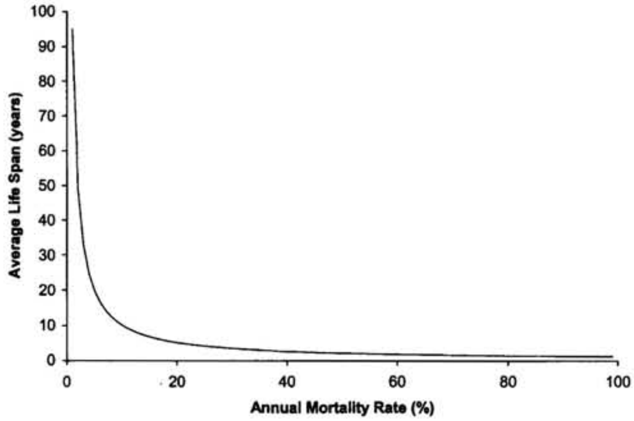

Fig. 3. Average tree life span given varying annual mortality rates.

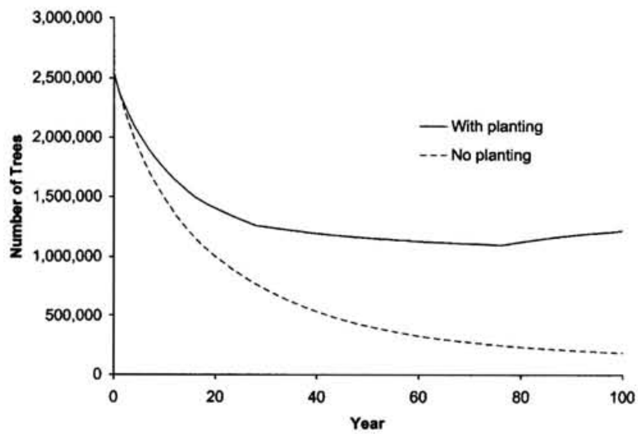

Fig. 4. Baltimore's projected tree population given existing diameter distribution and tree mortality rates in Table 3, assuming no new trees are planted or established (No planting) and assuming 42,650 trees are planted or established annually (With planting). Average dbh growth rate for Baltimore is estimated to be 0.63 cm/year.

Annual mortality rates also tend to increase as the condition of the tree worsened, with the only exception being trees in excellent condition that had an annual mortality rate of 9.2%, which was between trees in poor (7.7%) and critical condition (14.7%) (Table 5). To help understand why trees in excellent condition had a high mortality rate, the dbh distribution of excellent trees was compared to that of trees in all other condition classes (Fig. 1). Approximately 73% of trees in excellent condition were small trees less than 15.2 cm dbh. This rate compares to 63% for trees in other condition classes. It is likely that the trees in excellent condition had a relatively high mortality rate because of their small size, not their condition, as small trees exhibited significantly high mortality rates (Table 3).

Given a variable mortality based on dbh class (Table 3), the average life span of a tree in Baltimore would be 15 years with 30% of the population living past age 15. The percent of the population remaining after planting and average life span did not vary much with changes in dbh growth rates (Fig. 2). The average life span of trees drops significantly as annual mortality rates increase, particularly over the first 10–20 percent (Fig. 3). As an extreme example, if no new trees were established in Baltimore, the tree population would decline significantly over the next 100 years (Fig. 4) and the tree canopy would be sustained for about 5 years based on estimated average tree dbh growth (0.63 cm/year) (Fig. 5). Canopy growth projections vary with tree growth rates, but show a declining trend for dbh growth between 0.51–0.76 cm/year (Fig. 5).

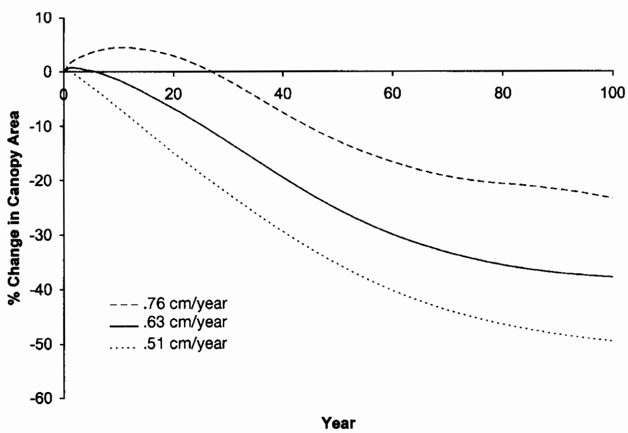

Fig. 5. Percent change in Baltimore's projected tree canopy area given existing diameter distribution and tree mortality rates in Table 3, assuming no new trees are planted or established with varying annual dbh growth rates. Average dbh growth rate for Baltimore is estimated to be 0.63 cm/year.

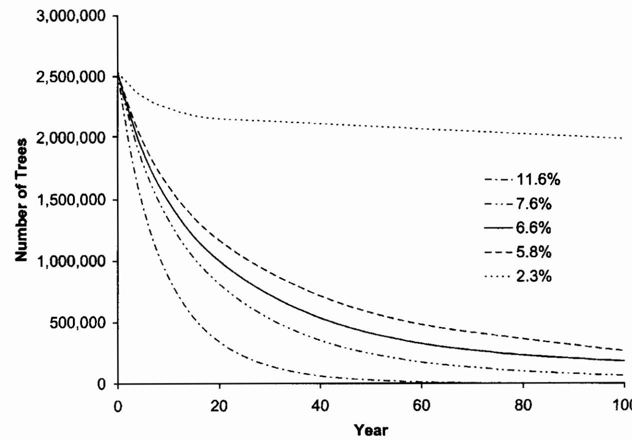

Fig. 7. Change in Baltimore's projected tree population given existing diameter distribution and 0.63 cm/year average dbh growth rate, with varying annual mortality rates assuming no new trees are planted or established.

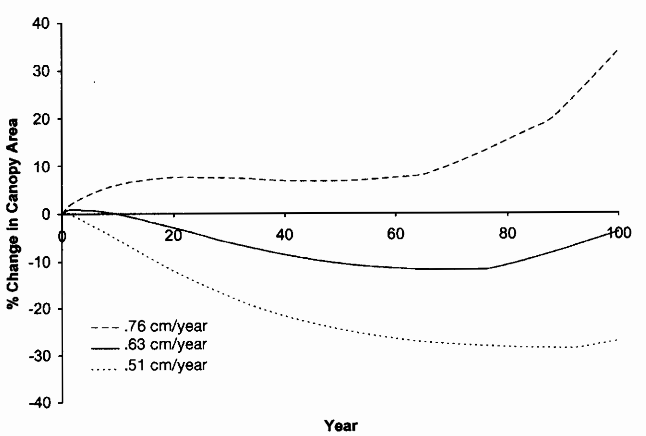

Fig. 6. Percent change in Baltimore's projected tree canopy area given existing diameter distribution and tree mortality rates in Table 3, assuming 42,650 new trees are planted or established annually with varying annual dbh growth rates. Average dbh growth rate for Baltimore is estimated to be 0.63 cm/year.

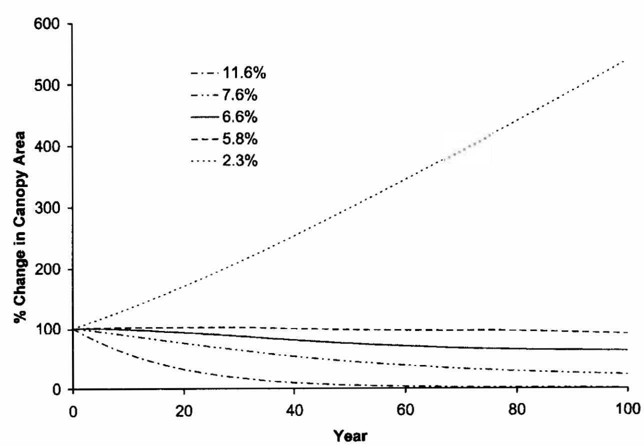

Fig. 8. Percent change in Baltimore's projected tree canopy area given existing diameter distribution and 0.63 cm/year average dbh growth rate, with varying annual mortality rates assuming no new trees are planted or established.

In 2001, 115,600 new trees were alive that did not exist in 1999, though some of the trees may have been less than 2.5 cm in dbh in 1999 and thus not measured as a tree. Most of these new trees were in forest (26.3%), institutional (19.9%), medium- to low-density residential (17.9%), and urban open lands (16.0%). These new trees are equivalent to an annual planting rate of 42,650 trees per year at a 9% annual mortality rate. Adding this annual planting/establishment to the tree population projections using a variable mortality based on dbh class (Table 3), Baltimore's tree population will decline to about 1.1 million trees after 75 years and then increase to around 1.2 million after 100 years (Fig. 4). With this new tree planting rate and an estimated average dbh growth rate, canopy cover is project to decrease after 10 years, dropping about 12% after 75 years, with about an overall canopy loss of 4% after 100 years (Fig. 6). Increasing dbh growth would lead to an increase in canopy cover; decreased growth would lead to a further decrease in canopy cover (Fig. 6).

Changing the tree mortality rate (± 1% or 5%) had a significant impact on tree population projections. A 1% or 5% decrease in some dbh classes could not be attained because base mortality rates were less than 1% or 5% respectively. A decrease of 1% mortality led to an average population mortality rate change from 6.6% to 5.8%; a 5% mortality decrease equated to an average population mortality of 2.3%.

Decreasing annual mortality rates from 6.6% to 2.3% leads to a change from 183,000 trees to 1,988,000 trees remaining after 100 years. Increasing mortality rates to 11.6%, leads to only 1,000 trees remaining after 100 years (Fig. 7). Decreasing annual mortality to 2.3% also leads to a significant increase in canopy cover after 100 years (540% increase), while increasing mortality from 6.6% to 11.6% changed the loss of original canopy cover after 100 years from 38% to greater than 99% (Fig. 8).

Discussion

Tree mortality is a significant factor affecting change in the urban ecosystem. Understanding rates and factors that affect urban tree mortality is critical to improving urban forest management to enhance environmental benefits and minimize tree costs and risk; and is essential for projecting future effects and benefits of the urban forest.

Four factors significantly affected tree mortality in Baltimore: tree size, tree health, tree species, and adjacent land use. Urban trees of small size or young age have been thought to have higher mortality than older trees due to establishment-related losses: those losses unique to young trees before they are established enough to survive minor accidents, vandalism, etc. (Richards 1979). Management (e.g., tree watering, fertilizing, protection, selection of quality trees) to reduce these establishment-related losses could significantly enhance the life-span and net benefits of urban trees. By reducing the annual mortality rate of trees less than 30.5 cm dbh in Baltimore to 3% (compared to values in Table 3), the average life of the trees more than doubled, increasing from 15 years to 33 years. Significant increases in average tree life span can be made by reducing annual mortality rates when mortality rates are less than 10% (Fig. 3). As it is very likely that urban tree mortality rates are less than 10% on average, management efforts to reduce mortality, including mortality associated with land-use change or development, will likely have a significant effect on sustaining urban forest canopy cover and benefits.

Mortality rates tend to increase on large trees and is likely related to senescence-related mortality: losses associated with aging (Richards 1979). The pattern of relatively high mortality rates of small and large diameter trees was exhibited in Baltimore and Syracuse's street tree population (Nowak 1986), though the actual rates differed.

Tree health is another factor that affects annual mortality rates. As tree health declines and percent crown dieback increases, the annual mortality rate tends to increase. This result makes sense as many factors that contribute to tree mortality (e.g., insects or diseases) are more prevalent on trees in poorer condition (Manion 1981). Also as tree health declines, more dead branches appear that increase the potential liability of the tree. As humans often manage the urban forest to limit liability and risk, trees in poorer condition have a greater probability of being removed. The pattern of increasing mortality with decreased tree health was also found for street trees in Syracuse, NY (Nowak et al. 2002).

In contrasting tree health with tree size, it appears that small tree size (or young age) may be a more significant factor affecting mortality than tree health. This supposition is based on the relatively high mortality rate of trees in excellent condition, which had a relatively high proportion of small trees. The mortality factors affecting these small trees are likely due to factors independent of tree condition (e.g., vandalism, accidental damage, establishment-related stresses).

Tree species was another factor that influences mortality rates. Four species were found to exhibit significantly high annual mortality rates: *Morus alba* (18.9%), *Ailanthus altissima* (17.6%), *Cornus florida* (13.2%), and *Acer negundo* (12.6%). *A. altissima* had 24.4% of its trees in the transportation land use and had a significantly higher mortality rate on this land use (35.1% annual mortality) than compared with high-density (3.6%) and low-medium density (0.0%) residential lands. Thus, the high mortality rate exhibited for *A. altissma* is likely due to this species' distribution among land-use types. *M. alba, A. altissima, A. negundo* are all considered as invasive plants (USDA, 2003) that often pioneer sites. *C. florida* is susceptible dogwood anthracnose (*Discula destructiva*), a significant disease that is found in Maryland that can kill infected trees (Cooperative Agricultural Pest Survey 2003).

The last significant factor that influences annual mortality rates is the surrounding land use. Land uses differ in the amount and type of activity around a tree, and the care or maintenance a tree receives. Land uses with relatively high mortality rates (transportation, commercial/industrial) typically have relatively low maintenance and intense activity (e.g., vehicle and pedestrian traffic) around a tree. These sites may encounter more tree damage from traffic and vandalism. In addition, these sites likely exhibit higher soil compaction due to the land-use activities and may not receive supplemental watering when young or during drought periods. Some land uses may also encounter rapid change or development that can lead to significant tree losses. These land-use related factors likely contribute to increased mortality rates.

In contrast, medium- to low-density residential areas exhibited low mortality rates. On these land uses, residential owners likely take greater care of their trees (e.g., watering, fertilization, tree protection), which can reduce mortality rates. This land use typically has a relatively low activity around a tree compared to other land uses. A sense of ownership of a tree also tends to lead to greater tree care and lower urban tree mortality rates (Sklar & Ames 1985; Nowak et al. 1990).

From the various studies of street tree mortality, it appears that the patterns of mortality in Baltimore based on tree size, tree condition and land use are similar, though the actual rates are different. Mortality rates in street tree populations, particularly when young, were often higher than exhibited in Baltimore, but studies of mortality of an entire street tree population in Syracuse, NY, was lower than that found for the entire tree population in Baltimore.

In terms of influences on tree mortality, it appears that a combination of environmental, social and species factors interact to determine mortality patterns and rates in cities. Management efforts to reduce environmental stress, particularly when the tree is young; improve tree care/reduce vandalism; and selection of the right tree for the right location could all help reduce tree mortality and sustain environmental benefits.

Population projections for urban trees are difficult due to limited information on urban tree growth, mortality, and natality rates. Given the mortality and natality rates found in Baltimore between 1999 and 2001, Baltimore's tree population and canopy cover is projected to decline over the next 100 years. These canopy projections are two-dimensional (based on crown width of living trees) and do not include the gradual decline of tree canopies through time, and thus likely underestimate actual loss in leaf area.

The results do reveal a general loss in tree population numbers and canopy cover, but these projections are dependent on the tree growth, mortality, and natality rates used. Tree growth rates can significantly affect canopy cover projections (Fig. 5 & 6), but have a limited effect on population totals (Fig. 2). Thus, enhancing tree growth can help offset canopy losses due to tree mortality. Tree mortality rate is another factor that can significantly affect both tree population totals and canopy cover projections (Fig. 7 & 8).

Slight changes in mortality rates have significant effects on tree population estimates, especially as the length of the projection into the future increases. The model projections of canopy change using reduced mortality rates (i.e., 2.3% annual mortality projected a 540% increase in canopy over 100 years) likely over estimates canopy change because as canopy area increases, crown competition and associated tree mortality are likely to increase. Thus, mortality rates can likely only be lowered for a certain period of time before compensating factors due to increased number of trees and canopy area (e.g., crown competition, insect outbreaks) tend to increase mortality and/or reduce growth rates. Model projections, particularly canopy area projections, are sensitive to both the growth and mortality rates used.

As there are very limited data on urban forest change, the projections become more uncertain the farther the projection into the future. Various factors in the future could significantly alter mortality and natality (e.g., significant land-use change, storms, large-scale tree planting programs), and thereby change the tree population projection. More long-term research is needed on urban forest growth, mortality and natality rates to provide more accurate estimates of future urban forest population totals and effects. Current population projections should be viewed with caution due to the high degree of uncertainty in projecting future tree populations in urban areas.

Conclusion

Baltimore's urban forest is currently on a decline, losing a net 4.2% of its live tree population between 1999 and 2001. Assuming the influx of new trees over the past few years is sustained, tree canopy cover is also projected to decline by up to 12% over next 100 years. Land use, tree size, tree species, and the condition significantly affect mortality rates and landscape change. Management efforts to sustain tree health and growth, and reduce mortality rates, particularly of small trees, could help sustain environmental benefits of urban trees over the long-term. Protection and management of trees in relatively high-use and/or low maintenance land uses such as transportation, commercial-industrial, and urban open can also help reduce overall urban forest mortality and sustain forest benefits across the city landscape.

Acknowledgments. This research was conducted as part of the National Science Foundation's Long-Term Ecosystem Research (LTER) project in Baltimore, MD. The authors thank Drs. Ralph Nyland and Robin Hoffman for their review of an earlier version of this manuscript.

References

Cooperative Agricultural Pest Survey (2003) Dogwood anthracnose. Available online at http://www.ceris.purdue.edu/napis/pests/dwa/; last accessed September 2003

Foster RS & Blaine J (1978) Urban tree survival trees in the sidewalk. Journal of Arboriculture 4(1): 14–17

Frelich LE (1992) Predicting dimensional relationships for twin cities shade trees. Department of Forestry, University of Minnesota. St. Paul, MN

Gilbertson P & Bradshaw AD (1985). Tree survival in cities: the extent and nature of the problem. Arboricultural Journal 9:131–142

Manion PD (1981) Tree disease concepts. Prentice-Hall, New Jersey

Nowak DJ (1986) Silvics of an urban tree species: Norway maple (*Acer platanoides* L.). State University of New York, College of Environmental Science and Forestry. Unpublished MS thesis. Syracuse, NY

Nowak DJ (1994) Atmospheric carbon dioxide reduction by Chicago's urban forest. In: Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. (Eds. McPherson EG, Nowak DJ & Rowntree RA): 83–94. USDA Forest Service, Northeastern Research Station, General Technical Report NE-186. Radnor, PA

Nowak DJ & Crane DE (2000) The Urban Forest Effects (UFORE) Model: quantifying urban forest structure and functions. In: Proceedings: Integrated tools for natural resources inventories in the 21st century. (Eds. Hansen M & Burk T), IUFRO Conference, 16–20 August 1998, Boise, ID: 714–720. USDA Forest Service, North Central Research Station, General Technical Report NC-212, St. Paul, MN

Nowak DJ, Crane DE, Stevens JC & Ibarra M (2002) Brooklyn's urban forest. USDA Forest Service, Northeastern Research Station, General Technical Report NE-290, Radnor, PA

Nowak DJ, McBride JR & Beatty RA (1990) Newly planted street tree growth and mortality. Journal of Arboriculture. 16(5): 124–129

Richards NA (1979) Modeling survival and consequent replacement needs in a street tree population. Journal of Arboriculture. 5(11): 251–255

Sklar F & Ames RG (1985) Staying alive: street tree survival in the inner-city. Journal of Urban Affairs 7(1): 55–65

U.S. Department of Agriculture, Natural resource Conservation Service (2003) Plants Database. Available online at http://plants.usda.gov; last accessed September 2003