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Tree compensation rates: Compensating for the loss of future tree values

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ABSTRACT

When healthy trees are removed, common methods of compensation are either monetary or replanting new trees. Accurate monetary compensation for large healthy trees is difficult to ascertain and often uses formulas based on tree attributes such as species, size, location and condition. Compensation based on leaf area is more direct as most tree values are related to healthy leaf area. Using leaf area, a tree compensation rate can be determined (how many new trees are needed to compensate for the removal of a healthy tree). However, compensation also needs to consider the future benefits provided by both the removed tree and newly planted trees. This paper provides a new method of tree compensation based on comparing the net present value of leaf area between a removed tree and planted replacement trees. This proposed method is not intended to replace existing methods, but rather facilitate discussion and science to improve estimating tree values and compensation. Using this new approach with a three-percent discount rate and a four- percent annual mortality rate, maximum compensation rates using comparable trees reached 13.7 trees for large trees and 3.3 trees for small trees. An overall maximum compensation of 41.1 trees was reached when large trees with a one-percent mortality rate were replaced with small trees with a four-percent mortality rate. Compensation rates vary with tree size, estimated life span remaining (mortality rate), discount rates, and type of replacement tree used (large vs. small trees). Compensation for tree loss can either be through planting of replacement trees or the conversion of replacement trees to a monetary value based on local planting costs.

1. Introduction

When a healthy tree is removed without permit or permission, one common question is: how should the tree owner or manager be compensated for the loss? Replacement costs are a direct means of compensation, but work best for small trees that can directly be replaced with the same size and species. For larger trees, formulas are often used to estimate replacement cost. Various formula methods exist, including: a) Council of Tree and Landscape Appraisers (CTLA) (CTLA, 2000), b) Standard Tree Evaluation Method (STEM) (Flook, 1996), c) Helliwell (2000), d) Norma Granada (Asociacion Española de Parques y Jardines Publicos, 1999), e) Burnley (Moore, 1991) and f) CAVAT (Doick et al., 2018).

These methods all use a measure of tree size (e.g., dbh or crown volume), condition and location to determine a tree value. Some methods (Helliwell and STEM) use a point system that is multiplied by a cost per point. The other methods use a cost per size (e.g., $/in^2 of dbh) with discounts (0–1 multipliers) for items such as life span, condition and location. With the Norma Granada method, some multipliers, such as condition, life expectancy and aesthetic value can increase the base value. Some methods, such as STEM, have specific criteria for tree functions such as pollution removal and temperature modification. While these approaches are conceptually similar, they can lead to vastly different estimates of compensation. In a study by Watson (2002), the average compensation among these approaches (excluding CAVAT) varied from $7,322 (Helliwell), $8,367 (CTLA), $45,624 (STEM), $57,343 (Burnley) to $77,971 (Norma Granada) for assessing the same trees (a 10.6 fold difference from lowest to highest). These valuation procedures provide a means to estimate the value of the trees based on its physical structure, but many procedures do not provide a means to estimate the value provided by tree functions (e.g., pollution removal, temperature modification, reduced building energy use, etc.) or the loss of future benefits.

Structural value is based on the physical dimensions of the asset (e.g., timber value), while the functional value is an annual value based on the functions of the particular structure. To understand the difference between structural and functional values consider a factory (with a replacement cost of $1 million) that produces 10,000 widgets per year with a net profit of $100,000/year. The value of the physical structure of the factory is based on the cost to rebuild or replace the factory with

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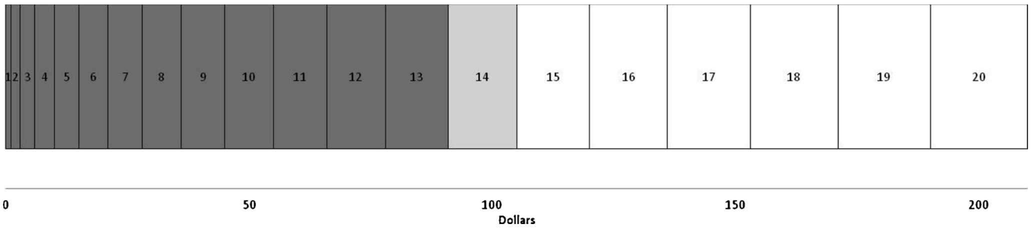

Fig. 1. Annual payments of $1 in year one, $2 in year two, $3 in year three and so forth for 20 years. Dark gray area is amount paid through 13 years; light gray area is amount paid in year 14 (current year); white areas indicate future payments.

a similar structure. The factory also has an additional value based on the potential or actual profits or losses of the factory outputs. The value of the factory structure ($1 million) is comparable to the structural value of the tree. The net profit ($100,000/year) is analogous to the functional value of the tree (Nowak et al., 2002a). Trees can have negative functional values (similar to monetary losses in factories) when the wrong tree is put in the wrong site (e.g., trees can increase annual building energy use in certain locations, tree pollen can create allergic reactions) (e.g., Heisler, 1986; Cariñanosa et al., 2014).

Annual functional values are critical for determining adequate tree compensation, as these functions (e.g., air temperature cooling, pollution removal) produce benefits that improve human health and well-being. The combination of multiple positive and negative functions (Dwyer et al., 1992; Nowak and Dwyer, 2007) provides a net annual functional value for a tree. The difficulty in ascribing an annual functional value to trees derives from limited quantification of these multiple benefits. As most of the functional benefits cannot be quantified and the ones that can be quantified often use estimated values (e.g., social costs, externality values, health care costs) to ascribe a monetary value, the means to determine the true monetary value of compensation is lacking or limited at best. If functional values cannot be adequately quantified and structural values are estimated in monetary terms based on formulas and replacement values, how can compensation for tree loss be ascribed that includes both structural and functional values of trees?

A solution to this problem lies in not trying to convert these values to monetary units, but in keeping the values in units that are directly related to the tree itself. The attribute that is most dominant in determining both the structural and functional value of trees is total leaf area (i.e., healthy canopy size). Large healthy trees provide abundant leaf area that remove air pollution, sequester carbon, intercept water, shade surfaces, cool the air, absorb ultraviolet radiation, provide food for wildlife, provide aesthetics and deliver multiple other benefits or costs to society (Nowak and Dwyer, 2007). In addition, large healthy trees also have the highest structural value due to their tree size, which is maintained through increased leaf area. As the value of the tree is most directly related to leaf surface area, then leaf area can be used to compensate for tree loss by directly compensating owners, not in monetary terms, but in terms of leaf area. That is, the number of small healthy trees can be calculated to provide a replacement for a large healthy tree by estimating compensation in terms of similar leaf area.

However, even if leaf area is used as a means of compensation, time must be considered in determining compensation rates. For example, if a large tree has 1500 m^2 of leaf area and a replacement tree has 30 m^2 leaf area, a compensation rate that does not consider time would be 50 replacement trees (1500/30). However, both the removed and replacement trees will live into the future, providing future benefits and values. The larger tree would likely have a shorter life span left, but more leaf area at the start relative to the smaller replacement trees; the replacement trees have a greater potential for future services as they grow through time. The replacement ratio of 50 trees would likely over compensate for the one removed tree due to the future potential of the smaller replacement trees. Thus, compensation based on leaf area should not only consider the amount of leaves from the removed tree and the replacement trees, but also tree growth (changes in leaf area through time), expected life span of the trees and the net present value of the future leaf area.

Existing estimates of compensation based on current tree diameter (tree size) are less appropriate as it compensates for past benefits already received or at best only current annual benefits. As trees age, they accumulate biomass, which increases tree diameter and leaf area (Nowak, 1994). Thus the biomass accumulated through time is an indication of the amount of past leaves and benefits received from the tree through its life to date. It is also an indication of current benefits, assuming that the tree is healthy, but it does not necessarily account for future benefits. For example, consider a person who promises to pay you $1 in year 1, $2 in year 2, $3 in year 3, and so forth for 20 years. At the end of 20 years, you would have received $210. If after 13 years the payments stop, you would have received $91, but would have lost current and future payments of $119. In Fig. 1, the dark gray areas of past payments are comparable to past benefits received by a tree (illustrated through cumulative tree growth to date). The light gray area in year 14 is comparable to current tree leaf area, which will increase tree diameter in year 14. The white areas indicate potential future leaf area and tree services. If a tree is removed in year 14, tree compensation should be based on current and future leaf area (light gray and white areas), not based on past growth as displayed by the tree diameter (dark gray areas), as these services have already been rendered (society has already received those benefits). Compensation based directly on tree diameter or crown size is compensating either for past services received (dark gray areas) or current services (light gray area).

What is critical in compensation is not what has been received in the past, but rather what will be received in the current and future years from the trees (light gray and white areas in Fig. 1). However, to compensate for lost future benefits, a reasonable remaining life span for a tree needs to be estimated for both the removed tree and the replacement trees. If a large tree only had one year remaining in its life, its compensation rate would be much lower than for a tree that has an estimated 50 years remaining. Likewise, compensation is reduced for replacement trees that have a long-life span vs. replacement trees that will have a short-life span.

The purpose of this paper is to determine compensation rates for the loss of healthy trees in terms of the number of replacement trees. This new approach is not intended to be a replacement to existing methods, but rather to provide a new means of quantifying compensatory value using lost future values. It is hoped that this new conceptual approach could be integrated within existing methods to improve tree valuation. This analysis uses varying tree sizes, mortality rates and discount rates to estimate the average number of replacement trees needed to compensate for the loss of healthy trees of varying size. The impact of tree size, life span and discounting rate are discussed, as is the conversion of replacement trees to monetary value.

2. Methods

The basis for compensation is the number of trees needed to provide the same amount of healthy leaf surface area of the removed tree, given that both removed and newly planted trees are expected to have healthy leaf area into the future. The compensation considers the discounted value of future leaf area as well as probabilities of future tree loss. The compensation rate is the number of newly planted trees needed to equal the net present value of leaf area for the removed tree.

To calculate this rate, the net present value (NPV) of leaf area of the newly planted trees and removed trees need to be calculated.

To determine the NPV of leaf area for a tree, four factors need to be considered: 1) leaf area, 2) life span, 3) growth rates, and 4) discount rate for future services. For this analysis, two types of tree sizes were assessed: 1) a large tree (represented by a London planetree; *Platanus* × *hispanica* Mill. ex Münchh.) and 2) a small tree (represented by crapemyrtle; *Lagerstroemia indica* L.).

2.1. Estimating annual leaf area

Leaf area of these trees was estimated based on leaf area formulas derived from tree crown parameters (Nowak, 1996; Nowak et al., 2008). The formula for estimating the leaf area of a tree was:

$$\ln Y = -4.3309 + 0.2942H + 0.7312D + 5.7217S + -0.0148C$$

where Y is leaf area (m^2), H is crown height (m), D is average crown diameter (m), S is the average shading factor for the individual species (percent light intensity intercepted by foliated tree crowns) and C is based on the outer surface area of the tree crown ($\pi D(H + D)/2$). To correct for logarithmic bias in the regression equations, a correction factor of one-half of the estimated variance was added to the untransformed value ($y = e^{x + var(x)/2}$) (Nowak, 1996).

An average shading coefficient (0.83) was used for both species as this modeling exercise was not trying to estimate the leaf area of a London planetree or crapemyrtle specifically, but rather an average for a large or small tree that used the crown dimensions of the planetree or crapemyrtle.

To estimate how leaf area changes with changing tree diameter at breast height (dbh – diameter at 1.37 m) or age, the relationship between crown dimensions and dbh needs to be estimated. To estimate crown height and crown width for these two species, allometric equations were developed from tree measurements from several U.S. cities. The equations used to estimate crown height were:

$$\text{Crown height (planetree, ft)} = e^{(1.6125 + (\ln(dbh) * 0.6897))}$$

$$\text{Crown height (crapemyrtle, ft): ht} = 4.8082 + (dbh * 1.6692)$$

The equations used to estimate crown width were:

$$\text{Crown width (planetree, ft)} = 3.9088 + 2.6747*dbh - 0.0329*dbh^2$$

$$\text{Crown width (crapemyrtle, ft)} = e^{(1.9526 + (\ln(dbh) * 0.3644))}$$

where dbh is in inches. As trees increased in dbh annually, crown dimensions and leaf area would increase based on these formulas. From the leaf area equation, an average leaf area index (LAI: ft^2 leaves (one-sided) /ft^2 projected crown ground area) was calculated based on the crown height to crown width ratio (Table 1). This LAI was multiplied by the estimated ground projected crown area (Πr^2 of crown) to calculate total leaf area.

2.2. Estimating life span

To estimate the life span remaining for the removed and replanted trees, a population projection model was used (Nowak et al., 2004). Four average annual mortality rates were modeled: 1, 2, 3, and 4 percent. For each of these projections, the annual mortality rates were varied by diameter class (Nowak, 1994), such that the average mortality rate for an urban forest population would equal the desired mortality rates (Table 2). That is, given an average dbh distribution, the mortality rate for each dbh class was adjusted so that the total mortality rate for the population was either 1, 2, 3, or 4 percent. The average dbh distribution for urban forests (Fig. 2) was based on field samples from 32 U.S. urban areas (cities or states). Mortality rates varied between dbh classes with higher mortality rates when small (young) and large (old).

Table 1
Estimated leaf area index based on crown height to width ratio and shading coefficient of 0.83 (Nowak, 1996).

Height to width ratio	LAI
2.0	7.6
1.9	7.1
1.8	6.6
1.7	6.1
1.6	5.7
1.5	5.3
1.4	4.9
1.3	4.5
1.2	4.1
1.1	3.8
1.0	3.5
0.9	3.2
0.8	3.0
0.7	2.8
0.6	2.7
0.5	2.6

Table 2
Annual mortality rates by dbh class for various life span classes.

	Average annual mortality			
dbh class (in/cm)	1 percent	2 percent	3 percent	4 percent
< 3 / < 7.62	1.2	2.3	3.5	4.7
3.01-6 / 7.63-15.24	0.9	1.8	2.7	3.5
6.01-12 / 15.25-30.48	0.8	1.7	2.5	3.4
12.01-18 / 30.49-45.72	0.8	1.7	2.5	3.4
18.01-24 / 45.73-60.96	1.2	2.3	3.5	4.7
24.01-30 / 60.97-76.2	1.2	2.4	3.6	4.8
> 30 / > 76.2	2.2	4.4	6.5	8.7

Using the population projection model, the average life span remaining for trees, based on current dbh, were modeled based on the input mortality rates by dbh class. Thus as trees grow through time, the probability of mortality would change. Based on the given mortality rates, the model will predict that no trees will remain after a certain dbh. However, in reality, if a large tree exists and is healthy, the probability of mortality in the next year would not be 100%. To limit the effect of an over-prediction of mortality for large trees, all healthy trees that are to be removed were given a minimum length of life span remaining based on mortality class. For 1 percent mortality, the minimum remaining life span for healthy trees was set to 20 years; for 2 percent mortality: 10 years; for 3 percent mortality: 8 years and for 4 percent mortality: 5 years. Based on the mortality rates (Table 2) and a 0.2 inch (0.51 cm) dbh annual growth rate, average annual life span can be estimated for each one-inch (2.54 cm) dbh class by projecting a large population through time using these rates (Fig. 3). Given a remaining life span in years, the annual projected leaf area values can be used to estimate the net present value of leaf area.

2.3. Tree growth rates

To estimate how leaf area will change through time as a tree grows, an annual trunk diameter growth rate of 0.2 in. per year (0.51 cm/yr) was used. This growth rate was selected to represent an average growth rate as temperate tree growth rates (153 day growing season) typically range between 0.15 in. / year (0.38 cm/yr) for forest-grown trees to 0.34 in. / year (0.86 cm/yr) for open-grown trees (Nowak, 1994; Nowak et al., 2002b). To estimate annual leaf area, tree dbh was increased annually by the growth rate and leaf area estimated for each year's tree dbh measurement. As a tree approached its estimated life span, annual growth rates were reduced. After the tree reached 75% of

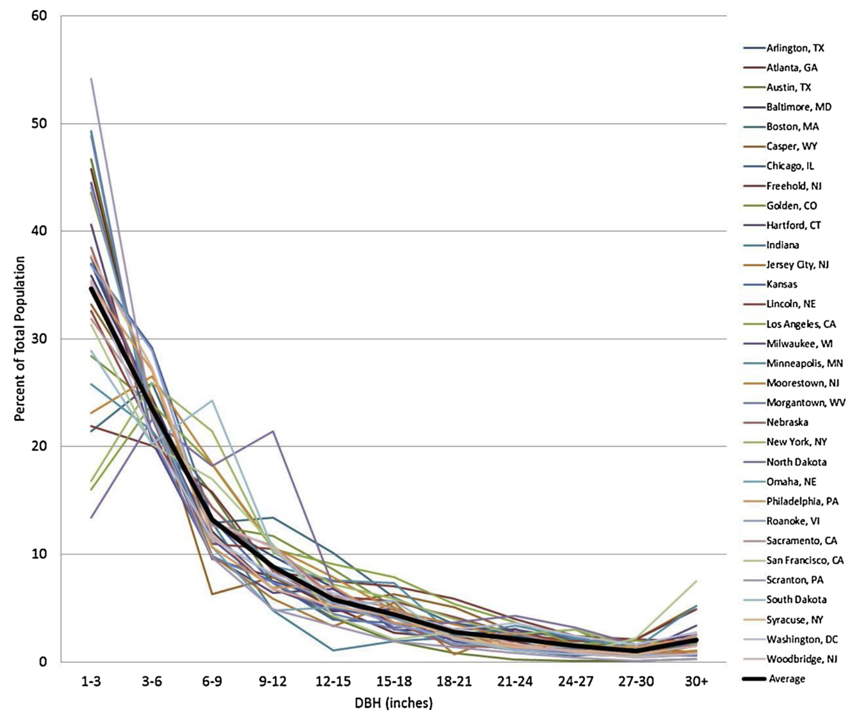

Fig. 2. Average diameter class distribution based on the diameter class distribution from 32 cities or urban areas in U.S. states.

its estimated life span, tree growth was reduced proportionally between 75% and 100%, such that at 75% of estimated life span tree growth was 0.2 in. per year (0.51 cm/yr) and at 100% of estimated life span tree growth rate was reduced to 0 in. per year. In addition, for the small tree, crown and leaf area growth was capped at a maximum dbh of 10 in. (25.4 cm), for the large tree it was capped at 45 in. (114.3 cm) dbh, such that crowns and leaf area did not change after that size, but remained steady.

2.4. Determining net present value of leaf area

The net present value of leaf area (NPV) was calculated as:

$$NPV = \sum_{i=1}^{n} LA_i/(1 + rate)^i$$

Where i = year beyond present year (present year = 1), n = number of future years, LA_i = leaf area in year i and rate = discount rate. To illustrate the impact of varying discount rates on NPV, three discount rates were used: 2, 3 and 4 percent.

2.5. Calculating compensation rates

The compensation rate (i.e., the number of one-inch (2.54 cm) dbh replacement trees needed to compensate for the loss of a healthy tree) was calculated as NPV_r / NPV_p, where NPV_r is the net present value of

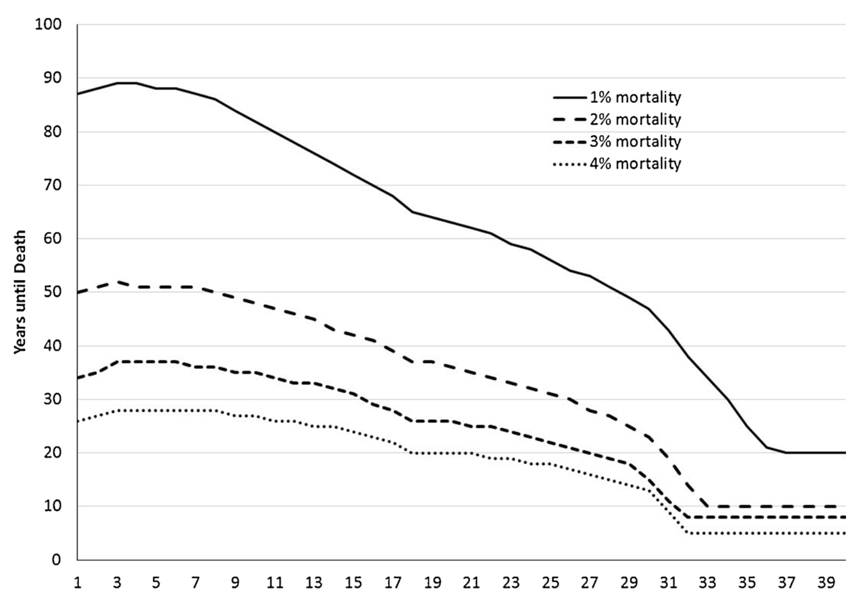

Fig. 3. Average life span remaining based on tree size among differing mortality rates based on a dbh growth rate of 0.2 in. per year (0.51 cm/yr). Remaining life span stabilizes after 30 in. (76.2 cm) dbh as healthy large trees are assumed to live a minimum number of years based on mortality rate.

leaf area of removed tree and NPV_p is the net present value of leaf area of a planted replacement tree. Average compensation rates were determined for each one-inch (2.54 cm) dbh class for differing tree sizes (large vs. small trees), life spans (1, 2, 3 and 4 percent average annual mortality rates) and differing discount rates (2, 3 and 4 percent).

2.6. Average mortality of residential trees

Data on tree mortality from randomly located plots in Baltimore, MD (Nowak et al., 2004) and Syracuse, NY (Nowak et al., 2013) were used to determine annual mortality rates for trees in residential areas. Data on tree change from 1999 to 2001 were used for Baltimore and 1999–2009 were used for Syracuse. The annual mortality rate was calculated as:

$$AMR = 1 - \sqrt[n]{N_n/N_0}$$

Where AMR = annual mortality rate (%), n = number of years between measurements, N_n = number of original trees remaining in remeasurement year n and N_0 = number of trees in original measurement year. Data from residential land uses (Baltimore: high-density residential and low-medium-density residential; Syracuse: residential and multi-family residential) were weighted by original tree population in the residential classes to determine the average mortality rates in the residential land use.

3. Results

Replacement rates vary depending on the remaining life span of the tree, the life span of the replacement trees, tree size and discount rates. The impact of discount rates was relatively minor with replacement values mostly exhibiting a slight increase (+1.1 trees) as discount rates increased from two to four percent. The average increase of replacing trees with similar-sized trees was between 0.1 trees for small trees with 4-percent mortality to 3.4 trees for large trees with one-percent mortality. Due to the minimal effect and the need to simplify the presentation of the remaining results, all results presented use a 3-percent discount rate.

Tree size and life span remaining had substantial impacts on the number of replacement trees. The large and small trees had large differences in projected leaf area through time (Fig. 4). The small tree attained maximum size for the allometric equations after 46 years and leaf area was held at its maximum after that point. This issue of attaining maximum size before 100 years has to do with the dbh cap that prevents small trees from attaining large dbh. The NPV between large and small trees also differ depending on life span remaining (Fig. 5).

When the estimated life span of the removed tree increases, the number of replacement trees increases. However, when the estimated life span of the replacement tree increases, the number of replacement trees decreases. In Supplemental Table 1, compensation rates are given for large trees being replaced by a similar large tree with a four-percent mortality rate. As dbh and life span of the existing tree increase, so does the compensation rate (Fig. 6). Compensation rates vary from zero trees for a one-inch (2.54 cm) tree with one year life span remaining to 43 trees for a 32-inch (81.3 cm) dbh tree with 100 years life span remaining. Similar tables with all tree size, life span and discount rates can be found at www.itreetools.org/research_suite/treecompcalc. This website also contains a calculator where the user can vary tree size, life spans remaining, and growth and discount rates to calculate the number of replacement trees and replacement values based on local planting costs.

Replacement rates also change when tree size classes are changed (Fig. 7). When replacing large trees with small trees, compensation rates increase. When replacing small trees with large trees, compensation rates decrease. When compensating with trees in the same size class, compensation rates for small trees are less than compensation rates for large trees. Maximum compensation rates for large trees replaced with large trees range between 6.6 (one percent mortality) to 13.7 (four-percent mortality); small trees replaced with small trees range between 1.8 (one percent mortality) to 3.3 (four-percent mortality); small trees replaced with large trees range between 0.9 (one percent mortality) to 2.5 (four-percent mortality); and large trees replaced with small trees range between 13.0 (two percent mortality) to 17.9 (four-percent mortality). Peak compensation of 41.1 trees was reached when replacing a large tree with one-percent mortality with a small tree with four-percent mortality (Table 3). Compensation varied with dbh and increases to a peak at 25 in. (63.5 cm) dbh for large trees and 10 in. (25.4 cm) dbh for small trees, and then decreased with larger sized trees.

Residential tree annual mortality rates in Baltimore and Syracuse were 3.6 and 3.8 percent respectively. If the high density and multi-family residential lands are excluded, residential tree mortality drops to 2.2 percent in Baltimore and 3.3 percent in Syracuse. Thus, reasonable

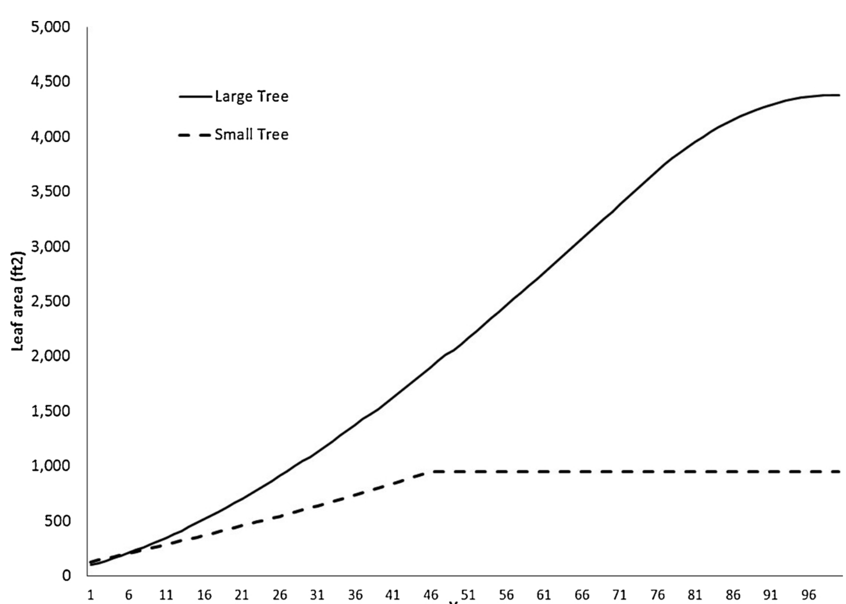

Fig. 4. Projected leaf area for large and small tree over 100 years.

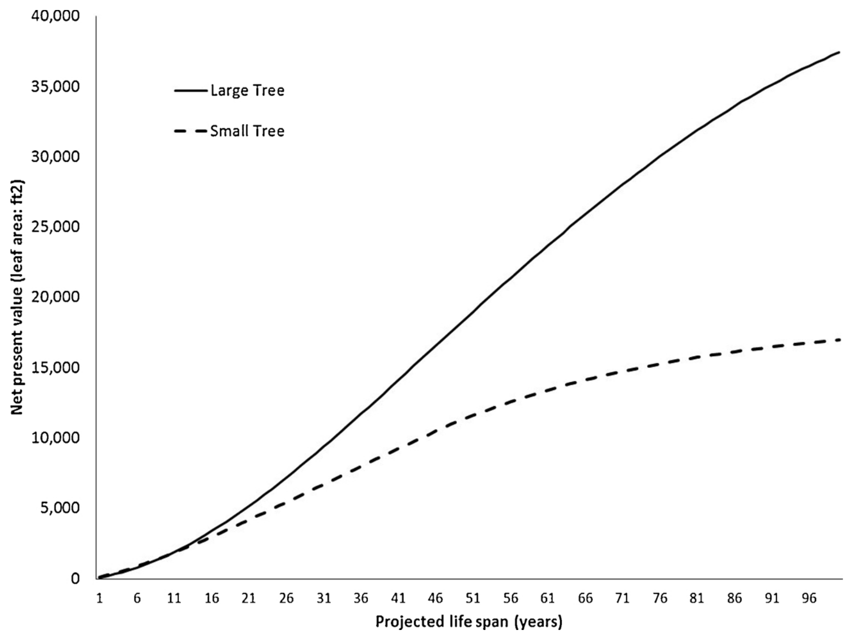

Fig. 5. Net present value of one-inch (2.54 cm) dbh tree (large vs. small) based on projected life span of the one-inch tree.

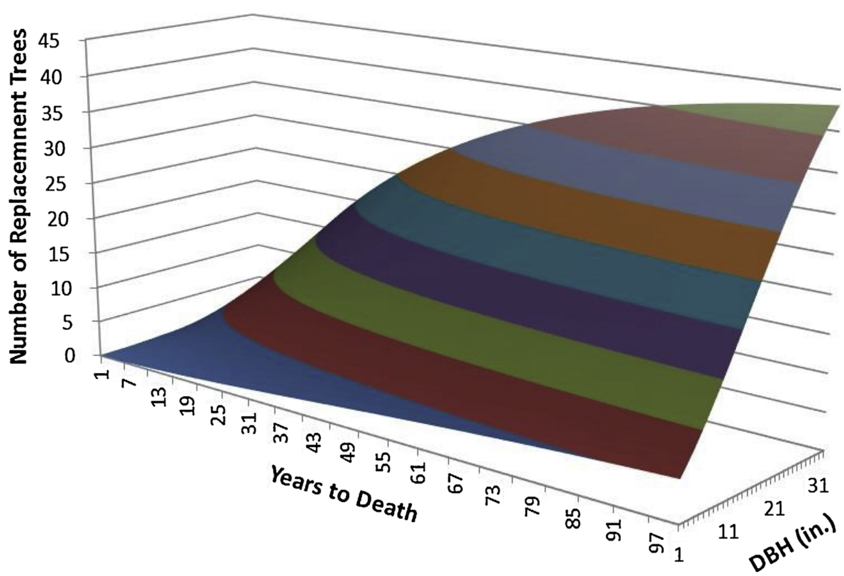

Fig. 6. Number of large one-inch (2.54 cm) dbh replacement trees with a 4 percent mortality rate needed to compensate for large tree loss based on dbh and estimated life span of existing tree. This figure is a graphic representation of data in Supplemental Table 1.

mortality rates for urban residential areas are likely between 2–4 percent annually. Mortality rates will vary among land use classes due to differences in such factors as development, environmental conditions, management/maintenance practices and competition. Using the four percent residential average for a typical mortality rate, general recommendations can be given on tree compensation rates based on tree dbh (Table 4). However, these are just general guidelines on compensation. With better local data and estimates on life span remaining, specific compensation estimates can be derived at www.itreetools.org/research_suite/treecompcalc using the size class tables with specific discount rates (2–4 percent; or 0–7 percent if the calculator is used).

4. Discussion

This paper proposes a new approach to estimating tree compensation for the loss of living trees. This approach bases compensation on the estimated loss of future functions, with compensation given in number of new replacement trees. Numerous other formula-based methods of estimating compensation exist, but this approach is fundamentally different. This new approach is not intended to replace existing methods, but rather set a foundation for improving existing methods.

4.1. Monetary conversion

The number of replacement trees can be converted to monetary units based on local market costs of replacement trees and the costs of planting the replacement trees. For example, a search of various tree nursery web sites finds that a reasonable cost for a one-inch (2.54 cm) dbh, 8–10 foot tall, ball and burlap replacement tree is $200 with replanting costs of $85 (Total = $285). Using this value and a 4% mortality rate (based on average residential mortality rates), the compensation value for large trees would range between $285 and $3,900 when replanting with a similar large species tree. Reducing the

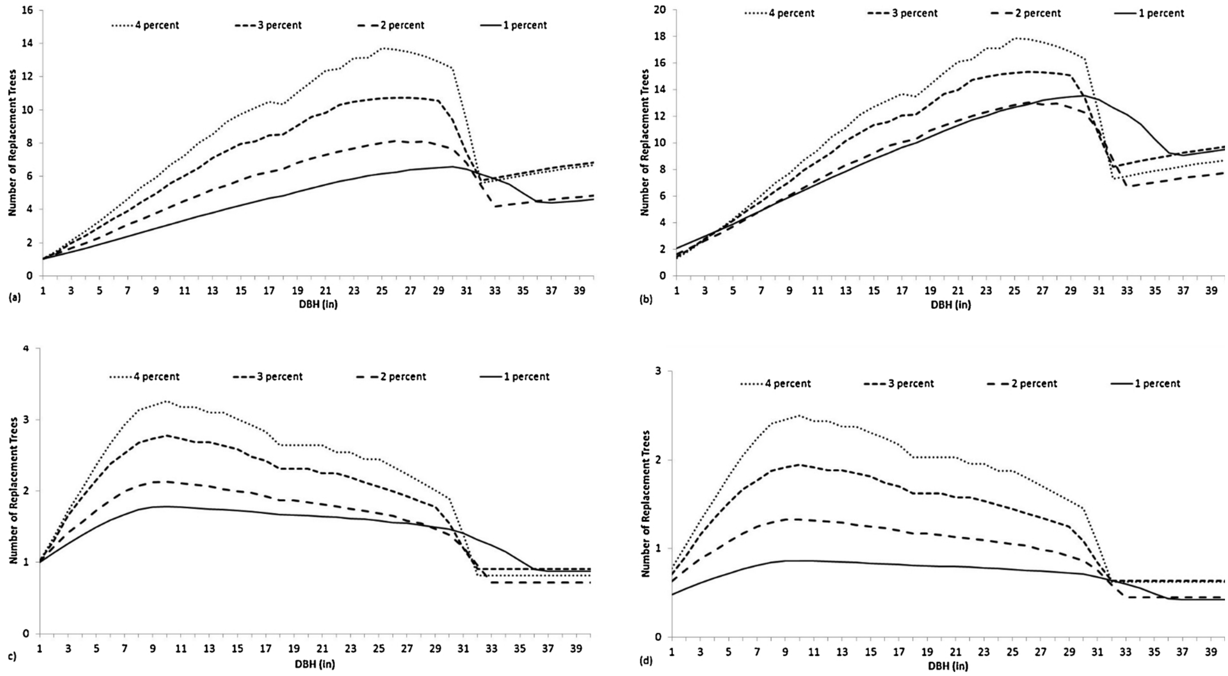

Fig. 7. Tree replacement rates by dbh of removed trees for varying mortality rates. The four percent line illustrates a tree with a four-percent mortality rate replaced with a tree with the same mortality rate and a dbh growth rate of 0.2 in. per year (0.51 cm/yr). Likewise for 3, 2 and 1 percent mortality lines. Figure (a) is a large tree replaced with large tree; (b) large tree replaced with small tree; (c) small tree replaced with small tree; (d) small tree replaced with large tree.

mortality rate would reduce the compensation. Maximum compensation will occur when a large tree with a 1% mortality rate is replanted with a large tree with a 4% mortality rate. In this case, compensation would range up to $9,000 per tree as the removed tree would have a longer expected life span. Valuation can range up to very large amounts depending upon the estimated life spans. For example, if a large 20-inch (50.8 cm) dbh tree with an estimated remaining life span of 100 years is to be replaced by large trees with an estimated life span of 10 years, compensation reaches 129 trees or $36,800. Minimum compensation could be $0 for dead trees.

4.2. NPV vs formula valuation

Compensation rates based on NPV of leaf area differ from the existing formula approach to valuation. As an illustration of differences in these approaches, the NPV approach is compared with the CTLA approach (CTLA 2000 9th Edition), one of the more conservative methods of valuation (Watson, 2002). While both approaches use dbh, the CTLA approach adjusts the replacement cost upward based on an estimated cost per unit trunk area for the trunk area that is greater than the area of the largest transplantable replacement tree. The tree value is multiplied by factors (0–1) for species, condition and location to determine the final value. In both approaches, the cost of tree and stump removal are separate from the compensation estimate.

These two approaches to valuation produce similar results for small trees up to around 10 in. (25.4 cm) in dbh, but can differ substantially for large trees with CTLA producing higher values. As an illustration, CTLA values were compared with the NPV approach for trees with $285 replanting costs, CTLA condition values of 1 (NPV approach also assumed healthy trees for this example) and CTLA species and location ratings of 0.8 and 0.2 (i.e., two estimates were made: one with species and location factors as 0.8, the other with these factors as 0.2) (Fig. 8). As NPV valuation is based on future values, as trees become larger, the compensation stabilizes and then slightly decreases as the large trees approach the estimated end of their life span. Using the CTLA approach the values increase with tree size as the core values are based on tree cross-sectional trunk area. In the CTLA approach, there is a trunk adjustment formula for trees greater than 30 in. (76.2 cm) dbh, so the estimated values in Fig. 8 would continue to rise, but at a diminishing rate.

Table 3
Maximum compensation rates by tree size and mortality rate for 3 percent discount rate. Bordered cells indicate trees within same size and life span class.

		Replacement tree							
		Large				Small			
Existing Tree		1%	2%	3%	4%	1%	2%	3%	4%
Large	1 percent mortality (1%)	6.6	12.2	20.9	31.5	13.6	19.5	29.9	41.1
	2 percent mortality (2%)	4.4	8.1	14.0	21.1	9.1	13.0	20.0	27.5
	3 percent mortality (3%)	3.4	6.2	10.7	16.2	7.0	10.0	15.3	21.1
	4 percent mortality (4%)	2.9	5.3	9.1	13.7	5.9	8.5	13.0	17.9
Small	1 percent mortality (1%)	0.9	1.6	2.8	4.1	1.8	2.6	3.9	5.4
	2 percent mortality (2%)	0.7	1.3	2.3	3.4	1.5	2.1	3.3	4.5
	3 percent mortality (3%)	0.6	1.1	1.9	2.9	1.3	1.8	2.8	3.8
	4 percent mortality (4%)	0.5	1.0	1.7	2.5	1.1	1.5	2.4	3.3

Table 4
Estimated compensation rates (number of one-inch (2.54 cm) dbh replacement trees) based on dbh of removed tree and average mortality for trees. Residential tree mortality in Baltimore and Syracuse averages 4 percent.

DBH	4% mortality				3% mortality				2% mortality			
(in/cm)	L > L	S > S	L > S	S > L	L > L	S > S	L > S	S > L	L > L	S > S	L > S	S > L
1/2.54	1.0	1.0	1.3	0.8	1.0	1.0	1.5	0.7	1.0	1.0	1.6	0.6
2/5.08	1.5	1.4	2.0	1.0	1.4	1.3	2.1	0.9	1.3	1.2	2.1	0.8
3/7.62	2.1	1.7	2.8	1.3	2.0	1.7	2.8	1.2	1.7	1.4	2.7	0.9
4/10.16	2.7	2.0	3.5	1.6	2.4	1.9	3.5	1.3	2.0	1.6	3.2	1.0
5/12.7	3.3	2.4	4.3	1.8	2.9	2.2	4.2	1.5	2.3	1.7	3.7	1.1
6/15.24	4.0	2.7	5.2	2.0	3.5	2.4	4.9	1.7	2.7	1.9	4.3	1.2
7/17.78	4.6	2.9	6.1	2.2	3.9	2.5	5.6	1.8	3.1	2.0	4.9	1.2
8/20.32	5.4	3.1	7.0	2.4	4.5	2.7	6.4	1.9	3.4	2.1	5.5	1.3
9/22.86	5.9	3.2	7.7	2.5	5.0	2.7	7.1	1.9	3.8	2.1	6.1	1.3
10/25.4	6.7	3.3	8.7	2.5	5.6	2.8	7.9	1.9	4.1	2.1	6.6	1.3
11/27.94	7.2	3.2	9.4	2.4	6.0	2.7	8.6	1.9	4.5	2.1	7.2	1.3
12/30.48	8.0	3.2	10.4	2.4	6.5	2.7	9.3	1.9	4.8	2.1	7.8	1.3
13/33.02	8.5	3.1	11.1	2.4	7.1	2.7	10.1	1.9	5.2	2.1	8.3	1.3
14/35.56	9.3	3.1	12.1	2.4	7.5	2.6	10.8	1.8	5.4	2.0	8.7	1.3
15/38.1	9.7	3.0	12.7	2.3	7.9	2.6	11.3	1.8	5.8	2.0	9.2	1.2
16/40.64	10.1	2.9	13.2	2.2	8.1	2.5	11.6	1.7	6.1	2.0	9.7	1.2
17/43.18	10.5	2.8	13.7	2.2	8.5	2.4	12.1	1.7	6.3	1.9	10.0	1.2
18/45.72	10.3	2.6	13.5	2.0	8.5	2.3	12.1	1.6	6.4	1.9	10.3	1.2
19/48.26	11.0	2.6	14.4	2.0	9.0	2.3	12.9	1.6	6.8	1.9	10.9	1.2
20/50.8	11.7	2.6	15.3	2.0	9.6	2.3	13.7	1.6	7.1	1.8	11.3	1.1
21/53.34	12.4	2.6	16.1	2.0	9.8	2.3	14.0	1.6	7.3	1.8	11.7	1.1
22/55.88	12.5	2.5	16.3	2.0	10.3	2.3	14.7	1.6	7.5	1.8	12.0	1.1
23/58.42	13.1	2.5	17.1	2.0	10.5	2.2	15.0	1.5	7.7	1.8	12.3	1.1
24/60.96	13.1	2.4	17.1	1.9	10.6	2.1	15.2	1.5	7.9	1.7	12.6	1.1
25/63.5	13.7	2.4	17.9	1.9	10.7	2.1	15.3	1.4	8.0	1.7	12.8	1.1
26/66.04	13.6	2.3	17.8	1.8	10.7	2.0	15.3	1.4	8.1	1.7	13.0	1.0
27/68.58	13.5	2.2	17.6	1.7	10.7	1.9	15.3	1.3	8.0	1.6	12.9	1.0
28/71.12	13.2	2.1	17.3	1.6	10.7	1.9	15.2	1.3	8.1	1.5	13.0	1.0
29/73.66	12.9	2.0	16.8	1.5	10.6	1.8	15.1	1.2	7.9	1.5	12.7	0.9
30/76.2	12.5	1.9	16.3	1.5	9.4	1.5	13.4	1.1	7.7	1.4	12.3	0.9
> 30/ > 76.2	6.5	0.9	8.5	0.7	6.4	0.9	9.2	0.7	4.9	0.8	7.8	0.5

L > L – large tree replaced with large tree; S > S – small tree replaced with small tree.
S > L – small tree replaced with large tree; L > S – large tree replaced with small tree.

The NPV approach differs from CTLA in how it handles differences among tree species, condition and location. The CTLA approach discounts species (0–1 multiplier) based on the rating of plant characteristics that include aesthetics, functional values, climatic and soil tolerances, resistance to insects and diseases, growth characteristics, maintenance requirements and allergenic properties. The NPV approach uses tree size class (large or small) and projected life remaining to estimate the current value of future services and aesthetics based on future leaf area. Growth characteristics are handled within the growth rate calculations, which can be varied in the calculator (www.itreetools.org/research_suite/treecompcalc). If the tree is replanted with the same species, all the positive and negative aspects of that

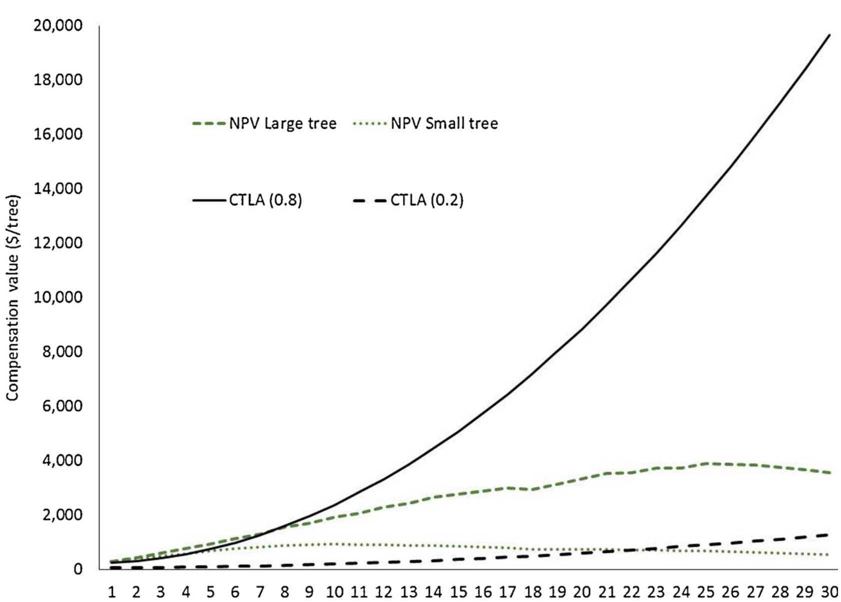

Fig. 8. Comparison of CTLA and NPV estimates for a one-inch (2.54 cm) replacement tree with a replacement cost of $285. CTLA basic price used was $43/in^2 based on U.S. national average values from 2000 adjusted based on the producer price index. The 0.8 adjustment estimates near maximum values from CTLA; the 0.2 adjustment is near the minimum values (minimum value could be $0 for a tree in very poor condition). Large and small tree compensation are based on a 4 percent mortality rate for both the removed and replanted trees, with replanted trees being of the same size class.

species, including maintenance and tolerances, will inherently be included. Thus, in converting to dollar values, the same species should be used as the species value will be directly accounted for in the cost of purchasing and planting of that species. If the same species cannot be purchased, then a close substitute that could be reasonably purchased would need to be found. In some cases, species may be classified as invasive and prohibited from sale or planting in certain regions. In these cases the compensation should be reduced as even though the invasive species would produce environmental benefits associated with leaf area (e.g., air temperature cooling, carbon sequestration), the species was deemed detrimental to the environment due to its invasive tendencies. These types of species adjustments could be done via local stakeholder agreements.

If for some reason the replanted tree needs to be a different-sized species, the number of replacement trees will change. For example, if a small tree is removed, the compensation may be in larger tree species, which would reduce the number of trees to be planted. Large trees replaced with smaller trees would require more trees to be planted. If the entity being compensated agrees to the species change, then changes in costs or values associated with the new trees (e.g., potentially increased maintenance costs) are irrelevant as the species change was agreed upon.

The CTLA approach discounts tree condition (0–1 multiplier) based on the rating of numerous health metrics. The NPV approach addresses condition based on estimated number of years remaining in which the tree would have remained healthy and functional. If the removed tree is dead, the estimated life span would be zero years and compensation would be zero trees. With decreasing vitality of the removed tree, there will be a concomitant reduction in life expectancy and compensation.

The current CTLA approach discounts location (0–1 multiplier) based on the rating of site, contribution and placement factors. The NPV approach does not directly address location, as all locations are treated equally. As far as possible, where site constraints do not preclude otherwise, the trees should be replanted in the same location when compensation is based on the number of trees. When converting the number of trees to monetary values, location could have an impact on the replanting costs. As property value often increases with trees (e.g., Sander et al., 2010; Saphores and Wei, 2012) and these changes in value are related to leaf area (e.g., McPherson, 2007), the NPV compensation should account for property value effects if trees are replanted on the same property. There could be a lag effect where property values may drop immediately after tree removal, but as the replanted trees grow, the property values would increase and may eventually surpass the original property value increase. As the property value change is only realized at the point of sale, on average the tree compensation related to property values should be adequate with some properties losing value and some gaining value depending upon when the property is sold relative to when the tree was removed.

This new approach fits well with the income approach using discounted cash flow analysis as discussed in the latest 10th edition of the CTLA guide for plant appraisal (Clark et al., 2018).

4.3. Limitations

While the NPV approach compensates based on future leaf area, it does not adequately account for future services that are location-specific. A good example of this type of service is tree effects on building energy, which depends upon where the tree is located in relation to the building. If a large tree on the west side of a residence is reducing annual energy use, the loss of that tree will not be adequately compensated as the multiple replacement trees cannot all be planted in the same location, thus not all of the replacement trees will produce the same energy effects. However, a change in compensation for these location-specific values is not likely needed as the additional replacement trees could have energy effects (e.g., shading of building, blocking winds) if planted near the building. In warmer climates, trees near buildings tend to reduce energy use through shade and air temperature cooling. In cooler climates, trees could have either positive or negative effects on energy use depending upon location relative to buildings (Heisler, 1986). Thus targeting the location of replanted trees is important for maximizing future building energy conservation.

With the exception of exotic invasive species removal, the NPV compensation should be considered a minimum compensation. The compensation is based on future leaf area, which is related to various services, values and aesthetics. It does not account for potential historical, social, crop or spiritual values of specific individual trees. These types of values would be tree specific and need to be determined as potential additional value. Examples of these types of values might be sentimental values associated with a tree planted by or in memory of a past family member, or the value of historical or spiritual trees (e.g., the treaty oak in Austin, TX; the survivor tree in New York City; the Major oak in Edwinstowe, England; the Bodhi tree in Bodh Gaya, India) (e.g., Kline, 2016). Pruning efforts used to create specialized tree crowns (e.g., topiary, pollarding, bonsai) would also not be compensated for using the NPV method. Loss of crop production (e.g., fruit and nuts) might be undercompensated due to the time lag in fruit production in newly planted trees. The NPV approach does not apply any type of punitive damage estimates associated with unlawful and willful removal of trees. The NPV approach also does not apply value to dead trees (zero years remaining in life span), yet dead trees can provide value through wildlife habitat, carbon storage and aesthetics. These potential adjustments are often subjective and could be determined locally on a per-tree basis based on local stakeholder agreement.

Another limitation of the NPV approach is the ability to estimate the remaining life span of the removed tree. Although estimates are provided based on estimated mortality rates, life span estimates can be improved through urban forest monitoring. Monitoring data can establish average mortality rates and thus life spans for different species under different environmental and land use conditions. In the United States, the U.S. Forest Service Forest Inventory and Analysis program has started to implement, in partnership with cities, long-term urban forest monitoring. This program measures urban forest data annually to assess urban forest structure, ecosystem services and values, and changes in structure, services and values through time. The first city to have completed a baseline inventory was Austin, TX (Nowak et al., 2016), with 28 cities monitored in 2018 and new cities to be added to the monitoring program in the next few years (US Forest Service, 2018). Though monitoring should provide better data on life span estimates based on species and dbh in the long run, in lieu of monitoring, local expert estimation of life spans could be a reasonable approach even though it is not science-based.

4.4. Factors affecting compensation rates

Based on limited existing urban forest monitoring data, a reasonable mortality rate for residential trees is currently 4 percent. This mortality rate includes not only the natural rate of mortality (removal of dead trees), but also the removal of healthy trees due to various human actions or choices (e.g., site development, people choosing to remove healthy trees for various reasons). Mortality rates will vary among land use types due to differences in mortality causes (e.g., development, plant competition, soil compaction) and tree care. The 4% mortality rate likely overestimates tree mortality due to more natural factors such as old age, insects and diseases and other natural environmental factors. However, these types of mortality factors may increase in the future due to the spread of insects and diseases, changes in climate and/or increased population pressures (e.g., Nowak and Greenfield, 2018). Tree maintenance activities such as watering to enhance young establishment (e.g., Vogt et al., 2015) and pest management strategies to reduce insect-caused tree death (e.g., Liu, 2017) could also help reduce mortality rates.

The 4% mortality rate is comparable to street tree mortality in West

Oakland, California (3.7%; Roman et al., 2013) and other street tree populations (3.5–5.1%; Roman and Scatena, 2011), but less than mortality rates for newly planted residential trees (6.6%; Roman et al., 2014) and newly planted street trees (19%; Nowak et al., 1990). Higher annual mortality rates among newly planted trees are accounted for within the mortality estimates (Table 2). However, if the establishment of new trees is difficult due to site conditions, the life spans of replacement trees should be reduced.

Though desirable, estimating the exact leaf area and life span of an individual tree is not essential for this process. What is essential is a reasonable estimate of leaf area based on tree size classes and estimating the species' average mortality rate. Not every tree species needs to be modeled for leaf area, rather species can be classified into size / crown density classes based on light interception coefficients and a representative tree species from that size class used to estimate leaf area for the class. For example, classes could be large trees with dense crowns (e.g., *Aesculus hippocastanum*), large trees with sparse crowns (e.g., *Gleditsia triacanthos*), small trees with dense crowns (e.g., *Acer ginnala*), etc. For mortality rates, generalized life span tables for a species could be created. Like actuarial tables used for life insurance, the exact life span of an individual does not need to be known, but rather the average life span for a species under various conditions (e.g., street side, parks) can be used to estimate average probable life span.

As the life span for replacement trees decreases (mortality rate increases), the compensation will increase. As the life span for removed trees decreases (mortality rate increases), the compensation will decrease. As large trees are already established, their mortality rate may be relatively low. New replanted trees will likely have a higher mortality rate due to establishment related mortality (e.g., Black, 1978; Nowak et al., 1990). Changing species between the removed and replanted trees may also change the mortality rates (e.g., replacing a long-lived species with a short-lived species). If this is the case, then using the same average mortality rate (e.g., 4 percent) for both the removed and replacement tree might not be sufficient. Increased mortality rates of replanted trees relative to removed trees would increase the compensation rate.

The mortality rate used in the NPV approach assumes an average mortality rate within three or six inch (7.6 or 15.2 cm) dbh size classes, with relatively high rates for smaller and larger trees. As trees shift size classes the rates change. Using the average mortality rates, the expected life spans tend to drop precipitously when the tree reaches the last dbh class (30+ inches (76.2+ cm)). Due to the relative high mortality rates in this last class (8.7 percent when using the 4 percent average mortality rate) and an assumption of a minimum life span remaining for all healthy trees, entering an estimated number of years remaining for trees greater than 30 in. (76.2 cm) is likely a better approach than using the estimated average mortality rate. Small tree species will likely not reach the 30-inch (76.2 cm) dbh class, so mortality of small trees may be underestimated and compensation overestimated using the average mortality data. More research is needed to develop more robust estimates of mortality rates and tree life spans.

Large trees require more compensation than small trees due to their greater leaf area. When replacing large trees with small trees, compensation increases; when replacing small trees with large trees, compensation decreases. Compensation for all trees regardless of size decreases as it reaches the end of its life span.

An average dbh growth rate of 0.2 in. per year (0.51 cm/yr) was used in this analysis. However, growth will affect compensation estimates as increased growth rates will increase leaf area. As growth rates of replanted trees are increased, compensation decreases due to increased leaf area, and vice versa.

If users are not interested in estimating compensation based on future values of leaf area, but would rather base compensation on replacing just current leaf area (i.e., the current leaf area of the replacement trees equals the current leaf area of the removed tree), the users can set the life span estimates in the calculator (www.itreetools.org/research_suite/treecompcalc) to one year for both the removed and replacement trees. In doing so, the current leaf area of the removed and replacement trees will be directly compared to estimate the number of replacement trees. In this case, replacing a large, healthy 30-inch (76.2 cm) dbh tree with a large one-inch (2.54 cm) dbh tree would require 80 replacement trees or $22,800 in compensation based on a planting cost of $285 per tree. Compensation rates will tend to increase without considering life spans and future values of trees, but the estimation process would be made much simpler by not requiring discount rates, and life span and growth rate estimates. This process would be a direct compensation for current leaf area.

As this proposed process is new, more research is needed to improve upon this procedure. There are four variables required to assess NPV: 1) leaf area; 2) growth rates; 3) life span remaining; and 4) discount rates. Leaf area is currently estimated from dbh based on two size classes (small and large trees). More size class evaluations for projecting leaf area would provide better refinements of estimates among species. Leaf area of removed trees can also be reduced downward based on percent crown dieback, as the leaf estimates are based on healthy trees. For example, if the removed tree has 50 percent crown dieback, compensation estimates should be halved, since half of the leaf area is missing. This dieback would also likely increase mortality rates, leading to a further decline in compensation.

Growth rate estimates could be improved with more urban forest monitoring, but current estimates are based on field data measurements and can be reasonably estimated. Discount rates are chosen by the user. Economists calculate that homeowners discount future benefits over 100 years at rates below 2.6% per year (Giglio et al., 2015). However, this rate is lower than the rates used by governments to assess infrastructure projects or by pension funds to evaluate their liabilities (Oxford, 2015). The most important variable to be improved upon is the estimate of life span remaining. This variable is critical. More forest monitoring to provide better estimates of average life span and mortality rates among various conditions (location, land use, etc.) would help improve estimates of compensation with this proposed method.

4.5. Suggested use

To use the NPV calculator or look-up tables, the following steps can be taken:

1) Measure dbh of removed tree and determine if tree is a large or small tree species
2) Determine the discount rate to be used. There are various ways to estimate a discount rate (e.g., judgment on projected rate of returns, current rate for US Treasury bonds). The three percent discount rate was used in this paper as it is the central value discount rate used in estimating the social cost of carbon (Interagency Working Group on Social Cost of Carbon, 2015). The two and four percent estimates are given to illustrate a range in values.
3) Estimate the number of years that the removed tree would have lived as a healthy tree if not removed (based on expert opinion). An option here is to use an average mortality rate (1–4 percent) if the number of years cannot be estimated. For large established trees, the mortality rate is likely lower than 4% for residential trees.
4) Determine size class of replanted tree species (large or small).
5) Estimate the average life span of the replanted tree. This average should be estimated based on the probability of survival. For example, if the replanted tree has a life span of 80 years, but only one in five replanted trees will live past five years due to establishment related mortality, then the average life span would be 20 years ((80 + 5 + 5+5 + 5)/5 = 20). An option here is to use an average mortality rate (1–4 percent) if the number of years cannot be estimated. The 4% mortality rate is currently recommended for residential trees.
6) Enter data into calculator or use look-up tables (www.itreetools.org/

research_suite/treecompcalc)

7) Convert the number of trees to monetary value based on local nursery and planting costs, if so desired.

5. Conclusion

This paper presents a new approach to tree compensation and valuation based on future services of trees. The results should be considered minimum compensation values and tend to be more conservative in the valuation of large trees than other approaches (e.g., CTLA, STEM, Burnley, Norma Granada) as the compensation values stabilize and do not increase with dbh after a certain size. Maximum compensation values tend to cap at $4,000 to $9,000 per tree depending upon the mortality rates used. The difficulty or limitation of this approach is knowing the likely remaining life span. Though estimates of life spans are given based on tree monitoring data and average mortality rates, life span estimation can be improved in the future through urban forest monitoring measurements. The current process uses two tree species to represent a large and small tree. More species equations could be added to represent leaf area projections for multiple tree size classes. This approach can be refined as more data become available and should work globally based on incorporating local costs and species information. The concept of valuation based on future services provides a better approach to valuation as the values are based on contrasting of future benefits rendered by the removed and replacement trees, not the current or past benefits as derived from dbh measurements or other approaches to tree valuation.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2019.03.014.

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