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Evaluating Urban Canopy Cover Before and After Housing Redevelopment in Falls Church, Virginia, USA

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Abstract. Local governments have created regulations aimed to maintain and increase valuable urban tree cover. The City of Falls Church, Virginia, USA, requires each residential redevelopment to retain or plant enough trees for 20% canopy cover within ten years. To assess whether this goal is being met, we studied 21 Falls Church residential lots redeveloped between 1994 and 2011 where existing houses had been replaced with larger ones. Initial tree inventories and measurements prior to redevelopment were recorded in redevelopment plans. We remeasured preserved and planted trees in a ground survey and modeled tree canopy growth from a periodic tree diameter growth model linked to a model relating tree and crown diameters. Geospatial analysis was used to calculate nonoverlapping canopy cover within lots from crown diameter measurements and/or model predictions. We found that the City of Falls Church generally met its 20% canopy cover goal, but that the canopy cover metric alone is insufficient to fully describe urban forest recovery. Although canopy cover might recover rapidly from planting many small trees, recovery to the larger tree sizes that maximize ecosystem services can take much longer. Our modeling of lot-scale growth from field measurements showed the potential to manage forests using traditional diameter-based forest metrics that would relate results to canopy cover when needed. These forest stand metrics—based on basal area and trees per hectare—can account for tree size changes masked by the canopy cover metric.

Keywords. Basal Area; GIS Buffer; GIS Dissolve; Municipal Tree Ordinance; Municipal Tree Policy; Quadratic Mean Diameter; Urban Forestry.

INTRODUCTION

Trees in cities provide essential environmental and economic services; these include reducing runoff, giving shade, enhancing aesthetics, harboring wildlife, and storing carbon (McPherson et al. 1997; Nowak and Crane 2002; Nowak et al. 2006). The overall vulnerability of urban forests, which are complex social-ecological systems, may be influenced by a variety of interrelated biophysical, built, and human components (Steenberg et al. 2017). Increased urban development typically results in increased impervious cover and decreased tree cover (Nowak and Greenfield 2012). Similarly, city expansion into surrounding forests fragments and reduces those forests and the services they provide; commuting and driving also increase, and attendant air pollution, road construction, and traffic congestion are exacerbated (Miller et al. 2015). One way to revitalize urban areas without clearing new land is to replace old houses with new ones. However, the long-term effects of redevelopment on the patchwork urban forest—such as the time needed for preserved and planted trees to restore the canopy cover that was present prior to construction—are only beginning to be studied (Berland 2012; Steenberg et al. 2018).

Local governments have created regulations that aim to maintain and increase the level of tree cover in cities (Hauer and Peterson 2015). Some cities have quite ambitious goals (Locke et al. 2017, Table 1). This produces a need to evaluate that tree cover (Bernhardt and Swiecki 1991; Abbey 1998; Zhang et al. 2009; Nguyen et al. 2017). Remote sensing techniques are frequently used for "top-down" assessments of urban canopy cover to address broad concerns, such as overall percent cover and changes over time, or to identify large areas of impervious surfaces (Berland 2012; McGee et al. 2012; Alonzo et al. 2016; Song et al. 2016; Locke et al. 2017). Complementary field-sampled "bottom-up" studies, while providing specifics about tree species, age, and condition, typically sample and assess limited areas because field measurements are costly and it is difficult to obtain access to generally private urban forest properties (Wiseman and McGee 2010; Alonzo et al. 2016). Therefore, few studies have addressed the effects of specific policies on urban tree cover based on detailed field measurements (Landry and Pu 2010; Roman et al. 2014).

Increased new housing construction within the area of northern Virginia near Washington, D.C., USA, generally follows the approach of replacing old houses rather than expanding urban boundaries. In Falls Church, Virginia, redevelopment is escalating, with existing houses being replaced by larger ones (City of Falls Church 2005), and most of the city forest is on private property (Walker 2015). An *i-Tree* ecosystem analysis (*i-Tree* 2017) based on a randomized field sample of public and private plots recently completed for Falls Church estimated 35% canopy cover overall (Wiseman and King 2012); a similar study evaluated street trees (Wiseman and Bartens 2012). However, neither of these assessments provided the kind of information necessary to evaluate, at the plot level, the city's existing policies that regulate canopy cover on private land.

Municipal management of trees is done less often on private property than on public lands (Conway and Urbani 2007), and can be difficult (Conway 2016), particularly in states with strong private property rights. However, in Falls Church the residential

Table 1. Lot-scale summary of urban forest data for trees on 21 lots in Falls Church, Virginia. Nonoverlapping canopy cover (cover), basal area (ba), trees per hectare (tph), quadratic mean diameter (qmd), and total above/belowground carbon (C) were calculated for inventory Time0 (including trees slated for removal as well as all others on the lot), Time1 (trees preserved and newly planted at time of redevelopment), and Time2 (field inventory 1–18 years after redevelopment). The variable *period* is the number of years between Time1 and Time2 inventories; Time0 was generally one year less than Time1.

Lot	Lot area (m^2)	Period (yr)	% Canopy cover			Basal area (m^2/ha)			Trees per hectare			Quadratic mean diameter (cm)			Total carbon (Mg/ha)		
			$Cover_0$	$Cover_1$	$Cover_2$	Ba_0	Ba_1	Ba_2	Tph_0	Tph_1	Tph_2	Qmd_0	Qmd_1	Qmd_2	C_0	C_1	C_2
1	1,551	11	53	7	22	18.7	1.8	5.8	109.6	96.7	96.7	47	16	28	36.6	2.4	8.1
2	855	1	80	28	29	19.9	8.0	8.5	175.5	128.7	128.7	38	28	29	24.8	7.5	7.9
3	1,213	10	35	32	41	11.1	9.7	13.1	49.5	65.9	65.9	53	43	50	18.0	16.3	22.8
4	1,540	8	49	0	28	22.0	0.1	4.0	58.4	279.2	279.2	69	3	14	46.3	0	4.1
5	1,707	9	56	48	63	13.2	11.6	17.8	210.9	246.0	246.0	28	25	30	33.2	30.7	42.8
6	1,176	6	82	50	56	50.1	32.4	36.8	221.2	144.6	144.6	54	53	57	77.2	50.9	58.6
7	687	7	64	64	75	14.9	15.0	17.1	14.6	58.2	58.2	114	57	61	15.6	15.6	18.0
8	639	8	80	0	7	31.2	0	0.8	140.8	46.9	46.9	53	3	15	28.6	0	0.4
9	970	15	41	0	51	6.9	0.1	7.9	41.2	185.5	185.5	46	3	23	7.7	0	7.3
10	855	11	28	0	29	10.4	0.1	2.7	140.4	105.3	105.3	31	3	18	8.4	0	1.8
11	584	6	3	2	13	1.0	0.7	2.5	119.9	308.4	308.4	10	5	10	0.2	0.1	0.7
12	1,091	14	51	43	58	16.1	12.6	17.8	229.2	412.5	412.5	30	20	23	18.8	14.7	21.6
13	1,297	3	85	30	33	31.4	5.2	6.0	316.1	84.8	84.8	36	28	30	51.1	8.8	10.0
14	582	11	55	5	26	11.3	0.6	3.7	86.0	171.9	171.9	41	7	17	8.6	0.2	2.0
15	994	12	44	30	51	13.8	9.6	19.0	110.6	231.3	231.3	40	23	32	17.1	10.3	21.5
16	972	14	8	0	6	2.7	0.1	0.7	92.6	185.2	185.2	19	3	7	2.2	0	0.4
17	1,100	5	44	36	43	19.4	14.8	19.9	181.8	163.7	163.7	37	34	39	26.3	19.8	28.0
18	1,439	9	19	1	13	4.2	0.3	1.5	62.5	111.2	111.2	29	6	13	6.0	0.2	1.5
19	790	13	62	5	35	16.7	1.0	6.8	101.3	113.9	113.9	46	10	27	18.9	0.9	6.7
20	1,229	18	80	15	59	31.9	4.6	18.4	366.1	268.5	268.5	33	15	30	54.8	4.4	22.6
21	1,008	1	77	11	14	24.1	3.3	3.7	267.8	89.3	89.3	34	22	23	33.3	3.9	4.1
Min	582	1	3	0	6	1	0	1	15	47	47	10	3	7	0	0	0
Max	1,707	18	85	64	75	50	32	37	366	413	413	114	57	61	77	51	59
Mean	1,061	9	52	19	36	18	6	10	147	167	167	42	19	27	25	9	14
SD	325	5	24	20	20	12	8	9	94	95	95	21	17	15	20	13	15

redevelopment process provides a private property management opportunity for the city government and allowed us to examine and assess the efficacy of one tree cover ordinance (cited in City of Falls Church 2008) as it applied to individual lots. According to the ordinance, landowners are required to retain or plant enough trees for 20% canopy cover on their property in 10 years. The ordinance is implemented through a site-specific redevelopment plan for each lot that must be approved by the city arborist and other city officials. Each carefully crafted plan is a legal document that addresses the architecture, drainage, sewer, utilities, and landscape of a proposed residential redevelopment and includes a tree inventory: a list of trees, by species, to be preserved, cut, and planted; diameter of those to be preserved and cut; and generally a sketch of tree locations on the lot's architectural map(s). The city arborist has two years beginning at redevelopment to enforce the plan; after two years, the homeowners—like any other homeowners—can do anything they wish to property landscaping and trees. Key to enforcement is knowing how long it takes various tree arrangements to reach 20% cover, but implementation guidelines provided by the city (City of Falls Church 2008; see especially pp. 6–9), partially based on nursery industry standards for open-grown tree species, lack documented scientific supporting information. Therefore, the Falls Church city arborist asked us to compare redevelopment plans to a current inventory to determine if tree arrangements approved under current guidelines are achieving the 20% goal and to develop a more scientific basis for projecting percent tree cover for future development.

Our study focused on comparing Falls Church redevelopment plans to current tree inventories on sampled lots where existing houses had been replaced by larger ones. The study objectives were to (1) determine if City of Falls Church urban forest management guidelines result in 20% canopy cover on a lot within 10 years after residential redevelopment, as mandated by ordinance, and (2) develop a lot-scale model framework for canopy growth projection after redevelopment using data from preserved and planted trees as input. We also explored the more traditional forestry metrics of basal area and quadratic mean diameter as complements to the canopy cover metric, because measurements and calculations for these metrics are simple and they appear to have potential for use in urban forestry (Kershaw et al. 2017).

METHODS

Study Area

The City of Falls Church is located within the Piedmont forest vegetation zone (Farrell and Ware 1991). Prior to development, white oak (*Quercus alba*) was probably the most abundant species, followed by other oaks, hickory (*Carya* spp.), tulip poplar (*Liriodendron tulipifera*), black gum (*Nyssa sylvatica*), and red maple (*Acer rubrum*); the latter three would have been more abundant on poorer acidic soils. Recovering Piedmont forests on about 100 plots in the surrounding counties are currently sampled by the Forest Inventory and Analysis Program (FIA 2015). These plots are mostly nonindustrial private ownerships, with some local, state, and federal government ownerships; none are managed for timber. The FIA-sampled forest plots are dominated by *Quercus* (mostly white oak), *Pinus* (mostly Virginia pine, *P. virginiana*), *Acer* (mostly red maple), *Carya* (mostly mockernut, *C. tomentosa*, and pignut hickory, *C. glabra*) and tulip poplar.

Although a complete inventory of public and private trees in Falls Church is lacking, a 2003 street tree inventory (on file with the City of Falls Church) shows the dominant genera are *Acer* (mostly red maple), *Quercus* (mostly red oak, *Q. rubra*, and willow oak, *Q. phellos*), *Cornus* (dogwood), and *Prunus* (cherry).

Sampling Overview

Two inventory datasets were compared: initial measurements from redevelopment plans and current remeasurements. Because redevelopment included the entire lot, we used the entire lot as the sample unit (i.e., basis of per-area statistics). Two types of lot-scale metrics were calculated and compared: a canopy cover metric and traditional forest stand metrics based on basal area and trees per hectare. These metrics were used for assessing canopy cover after redevelopment and to develop a framework for predicting canopy cover growth.

Twenty-one residential lots were selected from a list of more than 300 properties redeveloped in the City of Falls Church since 1994 (Figure 1). Random sampling was done within 6 classes that were defined by construction date to more heavily select lots with older construction dates and thus obtain more long-term growth data. Construction occurred between 1994 and 2011. Data from the initial redevelopment

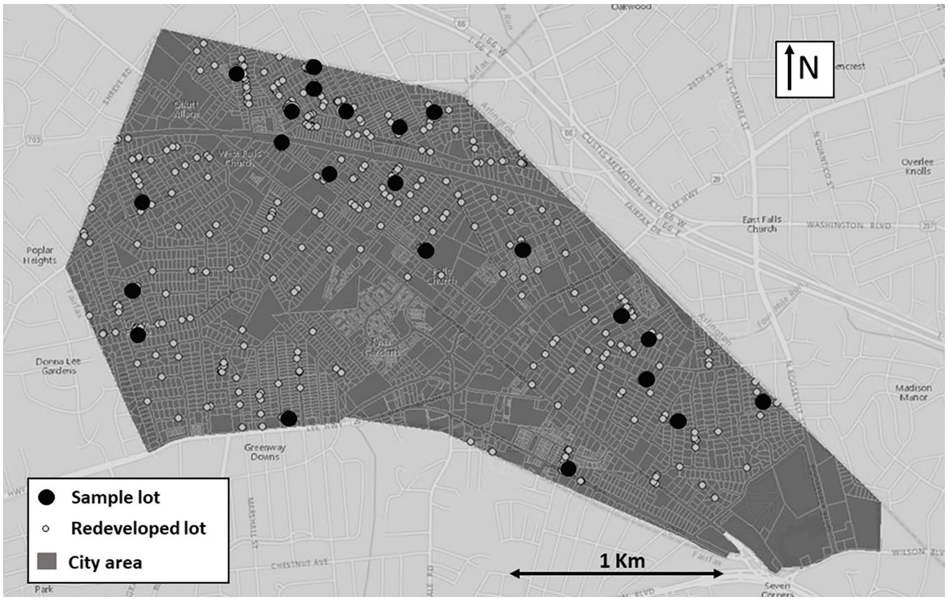

Figure 1. Map of Falls Church, Virginia, showing locations of 21 lots sampled for study (large black dots) among about 300 recent redevelopments. Falls Church is 5.3 square kilometers (2.1 square miles).

plan inventory and our field inventory up to 18 years after redevelopment were separated into three time periods: Time0, just before redevelopment; Time1, just after redevelopment; and Time2, the time of our field inventory. Time0 and Time1 separated the historical data (i.e., the data from redevelopment plans) into two categories for analysis. Time0 was the initial inventory of all trees identified on the plan and measured prior to redevelopment, both trees slated for removal and all others on the lot at that time. The Time1 inventory included trees preserved and those newly planted during redevelopment but omitted trees that had been removed during that process. Time1 was assumed to be 1 year after Time0, but Time1 was adjusted to the year the house was built if it was built later than a year after Time0 (determined from city records). All trees on the sample lots were remeasured in a ground survey at Time2 in 2012, 2013, or 2014.

Time0 and Time1 Inventory Data

For initial Time0 and Time1 inventories, redevelopment plans provided diameter (dbh), species, and rough location data from maps; if those trees were still present at Time2, their location was more precisely measured. We identified trees planted after redevelopment from redevelopment plans, but supplemented and verified these identifications with Time2 field observations, because plans were not necessarily adhered to for all lots. Precision of tree diameter measurements on plans was not identified, but trees appeared to have been measured or estimated to the nearest 2.5 to 5 cm (1 to 2 inches). Measurements of all preserved trees at Time1 were assumed to be the same as for Time0, and newly planted trees were assumed to have a dbh (diameter at breast height, 1.3 m aboveground) of 2.5 cm (1 inch) and a crown area of zero. Redevelopment plans omitted crown measurements, which had to be modeled for initial Time0 and Time1 inventories as described below.

Time2 Inventory Data

Field measurements at Time2 included tree species; diameter to the nearest 0.25 cm (0.1 inch); crown diameter (two roughly perpendicular measurements to the nearest 0.3 m [1 foot]); and geographic coordinates of each tree, measured perpendicular from the two closest lot boundaries for manual transfer onto lot boundaries in a geographic information system (GIS) environment. All diameters were measured at dbh except for some multiple-stemmed species that branched profusely at dbh; in those cases, diameters were measured at ground line just above the root collar (drc) and adjusted to dbh as described below.

All nonoverlapping crown cover and all per-hectare calculations were based on GIS base maps for lot areas using scanned copies of original architectural redevelopment plans on file with the City of Falls Church. Because the city right-of-way was not always labeled clearly on redevelopment plans, calculated lot areas differed slightly (maximum about ± 8%) from those supplied by city property tax records; for consistency, our calculated lot area was used.

Diameter was measured at dbh for single-stemmed trees but was calculated as

$$\left(\sqrt{\sum_{i=1}^{n} d_i^2}\right)$$

for multiple-stemmed trees from individual-stem diameters (d_i)(Batcheler 1985). Because all analyses were done at dbh, a drc-to-dbh conversion model was needed for 56 trees (on 14 lots) only measured at drc (Chojnacky and Rogers 1999); the genera of these trees were *Acer*, *Amelanchier*, *Cercis*, *Lagerstroemia*, *Magnolia*, *Taxus*, *Picea*, *Prunus*, and *Ulmus*. This need was anticipated; subsamples for all tree sizes and species were measured at both drc and dbh. A model was constructed from data from 163 subsampled trees from the needed genera (dbh = -0.8399 + 0.8244 drc + 1.7648 I_L + 1.0336 I_P; *where* diameters in cm, I_L = 1 for *Lagerstroemia*, 0 *otherwise*; I_P = 1 for *Prunus*, 0 *otherwise*; (R^2-statistic = 0.93; data limit dbh < 40 cm).

Crown area at Time2 was computed as a circle by using crown diameter calculated as the geometric mean of crown diameter (c_1, c_2) measurements $\left(\sqrt{(c_1)(c_2)}\right)$.

Crown Modeling

Crown diameter was modeled for 217 cut and 125 preserved trees in initial Time0 and Time1 inventories because redevelopment plans lacked crown diameter measurements. A separate crown diameter (crndia) model was developed from Time2 inventory data for each of the 21 lots, which averaged approximately 25 trees per lot (lncrndia = $ß_0 + ß_1 ln$dbh + $ß_0 I_{eh} ß_0 I_c$; *where* I_{eh} and I_c are indicator [0,1] variables for evergreen hardwood and conifer species respectively; R^2-statistics = 0.80–0.99, median = 0.94). To avoid illogical extrapolations when all Time2 inventory trees for a given lot were considerably smaller than initial inventory cut trees (as was the case for 10 lots), a few large trees from neighboring lots that matched the species in question were included in the estimation.

Calculations of crown diameter worked well in later analysis after including a modification, motivated by some cases where calculated canopy growth for preserved trees was negative (particularly when the interval between Time1 and Time2 was less than 10 years). The modification used an adjustment ratio based on regression residuals from the crown diameter model. For each preserved tree, actual measured crown diameter at Time2 was divided by a model estimate of crown diameter at Time2; the Time1 model-estimate of crown diameter was then multiplied by this ratio. If the Time2 ratio was less than one, then the model predicted high, and the ratio multiplication reduced the Time1 estimate; similarly if the ratio was greater than one, the model predicted low, and Time1 crown diameter was adjusted upward by the ratio. The ratios ranged from 0.4 to 1.9, but most (25th to 75th percentiles) ranged from 0.91 to 1.12.

Canopy Cover Calculations

We calculated nonoverlapping canopy cover on each lot from individual geographically located tree crown areas using a series of ArcMap™ geoprocessing tools—*Buffer*, *Dissolve*, *Union*, and *Clip* (i.e., within a lot boundary, half the area of overlap from the union of circles corresponding to the crowns was excluded). The total nonoverlapping cover within a lot was divided by the total lot area (total area of open space and nonoverlapping canopy) with no exclusions for the house footprint and expressed as percent canopy cover.

Cover from trees spreading into neighbor lots was excluded, as was cover from neighbors' trees or street trees extending into the sampled lot; this was consistent with the canopy cover definition used by the City of Falls Church and appeared reasonable. A paired *t*-test using data from 3 of our 21 sampled lots showed no significant difference between nonoverlapping cover from within-lot trees that extended over a neighbor's lot and that from neighbor trees that extended into the sampled lot. Only 3 lots were analyzed because comparison was limited to lots where all neighbor trees extending into a sampled lot had both measured field data and geolocated coordinates; these were difficult to obtain because access permission was required from all surrounding neighbors while in the field.

Calculations of Other Metrics

Also calculated for each lot were basal area (ba, sum of cross section area of trees at dbh in m^2 divided by lot area in hectares), trees per hectare (tph), and quadratic mean diameter for an estimate of average tree size (qmd = [200 $\sqrt{ba/(\pi \cdot tph)}$], in cm)(Curtis and Marshall 2000; Kershaw et al. 2017). In addition, carbon (assumed to be 50% of biomass) was calculated (Chojnacky et al. 2014) for interpreting results. These metrics were developed for traditional forestry, so caution should be exercised when using them in urban forests in ways beyond the scope of this study; for example, modifications might be needed in our use of the entire lot (including impervious surfaces) as the basis for calculations.

Analysis

The preliminary calculations above and statistical analyses were conducted using SAS/STAT® software version 9.4 (SAS Institute Inc., Cary, North Carolina, USA) and spatial analysis was done with ArcMap™ software version 10.3.1 (Esri, Redlands, California, USA). SAS/Graph® was used to create statistical graphics. Statistical testing assumed a significance level of 0.05. Because each lot was considered a sample unit, tree data were summed to per-hectare lot-scale for analysis (Table 1).

Objective 1: Lot-scale Canopy Cover Assessment

An estimate of canopy cover 10 years after redevelopment for each lot was obtained by assuming a general canopy growth curve as a function of time since redevelopment (period, or years, between Time1 and Time2), "indexed" to growth on each specific lot: *ln*c-growth = $ß_0$ + $ß_1$*ln*period + $ß_0$index, *where*: c-growth = $cover_2 - cover_1$, period = years since redevelopment, index = c-growth / period, *ln* = natural log (Table 1). This canopy growth curve was first fit to data (*ln*c-growth = -0.5633 + 0.9898 × *ln*period + 0.5833 × index; R^2-statistic = 0.98, n = 21). Then 10-year adjusted data were obtained by solving the equation for 10 years after redevelopment (*ln*period = *ln*10 = 2.3026). Cover at year 10 for each lot was then calculated by adding canopy cover at redevelopment ($cover_1$) to the 10-year growth prediction from the equation. We hypothesized that this calculated canopy cover at year 10 would be greater than 20%; a one-sided *t*-test was used to test this hypothesis ($H_0 = 20$, $H_A > 20$).

After statistical testing was conducted, statistical graphics were created to help interpret the entire sample distribution: canopy cover was easily compared to other metrics, and the graphs provided the perspective of "years since redevelopment" for each lot or inventory period.

Objective 2: Lot-scale Model Development

Modeling was done in two parts with per-hectare scale data (Table 1): (1) canopy cover predictions were developed from basal area (Mitchell and Popovich 1997), and (2) average basal area growth was estimated so that canopy growth could be projected.

The correlation between nonoverlapping canopy cover at Time2 and basal area at Time2 was the basis for modeling canopy cover predictions from basal area, but the model also included quadratic mean diameter (qmd) at Time2 and an indicator variable to separate growth rates for planted trees from those for preserved trees. The model was fit using robust regression (regression modification where effects of outliers minimized; SAS Institute Inc. 2016).

To model basal area growth, we defined *average annual* growth as the difference between Time1 and Time2 basal area divided by years between Time1 and Time2 (or period in Table 1). We separated data into four major categories—planted and preserved trees within deciduous and evergreen (hardwood and conifer) classes—to group basal area for these categories into similar ranges. A model was then fit to each category to estimate an average annual basal area growth rate from Time1 basal area. Robust regression and log transformations were used to estimate parameters; regression was aimed at prediction only, so our primary interest was evaluating the model with respect to data fit rather than other regression diagnostics.

The following were computed from Table 2 equations in order to examine the overall statistical fit of data modeling:

1. Average annual basal area growth (bag) of each lot was estimated from equations for the respective categories ($\widehat{bag}_{dpr}$, $\widehat{bag}_{epr}$, $\widehat{bag}_{dpl}$, $\widehat{bag}_{epl}$, for deciduous preserved, evergreen preserved, deciduous planted, and evergreen planted, respectively).
2. Basal area at Time2 was estimated from basal area growth model results multiplied by the period between Time1 and Time2 in years (1 to 18) and added to Time1 basal area (for example, ($\widehat{ba}_{dpr2} = [\widehat{bag}_{dpr} \cdot \text{period}] + \widehat{ba}_{dpr1}$).

Table 2. Model parameters for projecting canopy cover from basal area (ba) growth. Modeling was done in two parts: (1) canopy cover predictions were developed from basal area, and (2) average basal area growth was estimated so that canopy growth could be projected.

Component variable	$ß_0$	$ß_1$	$ß_2$	$ß_3$	n	R^2
Canopy cover (%)	0.9796	0.7221	0.4353	-0.9319	21	0.81
Ba growth (m^2/ha/yr):						
Deciduous preserved (bag_{dpr})	-1.9221	0.3582			14	0.48
Evergreen preserved (bag_{epr})	-2.3942	0.6830			11	0.31
Deciduous planted (bag_{dp})	1.4720	1.0697			21	0.55
Evergreen planted (bag_{ep})	-0.5290	0.7915			17	0.41

Where:

cover $= Exp[\beta_0+\beta_1 ln\text{ba}+\beta_2 ln\text{qmd}+\beta_3\text{I}]$; ba = basal area ($m^2$/ha);

qmd = quadratic mean diameter (cm); I=1 for preserved, 0 planted

$bag_{dpr} = Exp[\beta_0+\beta_1 ln\text{ba}_{dpr}]$; ba_{dpr} = deciduous preserved basal area (m^2/ha)

$bag_{epr} = Exp[\beta_0+\beta_1 ln\text{ba}_{epr}]$; ba_{epr} = evergreen preserved basal area (m^2/ha)

$bag_{dpl} = Exp[\beta_0+\beta_1 ln\text{ba}_{dpl}]$; ba_{dpl} = deciduous planted basal area (m^2/ha)

$bag_{epl} = Exp[\beta_0+\beta_1 ln\text{ba}_{epl}]$; ba_{epl} = evergreen planted basal area (m^2/ha)

3. Basal area at Time2 was summed for deciduous and evergreen trees for preserved and planted tree classes (for example, $\widehat{ba}_{pr2} = \widehat{ba}_{dpr2} + ba_{epr2}$).
4. Quadratic mean diameter at Time2 was calculated for preserved and planted trees ($\widehat{qmd}_{pr2}$, $\widehat{qmd}_{pl2}$, respectively) from the above basal area estimates and trees per hectare for each lot.
5. Finally, canopy cover was estimated at Time2 for each lot (from Table 2 cover equation) by using the above calculations of basal area and quadratic mean diameter as Time2 predictor variables.

We then compared canopy cover predictions to actual data for Time2 (actual minus predicted in a residual graph).

RESULTS

Objective 1: Lot-Scale Canopy Cover Assessment

Statistical Testing

Canopy cover was significantly larger than 20% ten years after redevelopment (one-sided *t*-test; $H_0 = 20$, $H_A > 20$; mean = 37%, *P*-value = 0.0002). However, the canopy cover at redevelopment Time1 (crown_1) of preserved and planted trees was not significantly different from 20% (one-sided *t*-test; $H_0 = 20$, $H_A < 20$; mean = 19%, *P*-value = 0.4450); in other words, since the mean lot cover was near 20% from preserved trees at redevelopment Time1, it was not surprising cover exceeded 20% after 10 years.

Statistical Graphics

A statistical graph (Figure 2) shows lot details for the three inventory periods compared to the ordinance objective of 20% canopy cover after 10 years. Canopy cover prior to redevelopment was as high as 85% (mean 52%, sampling error 21% of mean at 95% confidence); only 3 lots had cover below 20%. Although the mean canopy cover at Time1 (cover_1), time of redevelopment, was 19% (46% sampling error; not significantly different from 20% as shown above), about half the lots were cut back to nearly 10% cover or less while the other half retained approximately 30% cover or more.

Ten of the 21 lots sampled were remeasured at least 10 years after redevelopment and only one had canopy cover at Time2 below 20% (Figure 2; mean 36% with 24% sampling error). Eleven lots were remeasured less than 10 years after redevelopment; only 4 of these had cover less than 20% and most of those appeared likely to meet the 20% goal. However, only 8 of 21 lots showed canopy cover at Time2 greater than that prior to redevelopment, and these were primarily lots where canopy cover had not been severely reduced or that had had more than 10 years to recover. In sum, graphical results suggested further examination of the data might be worthwhile.

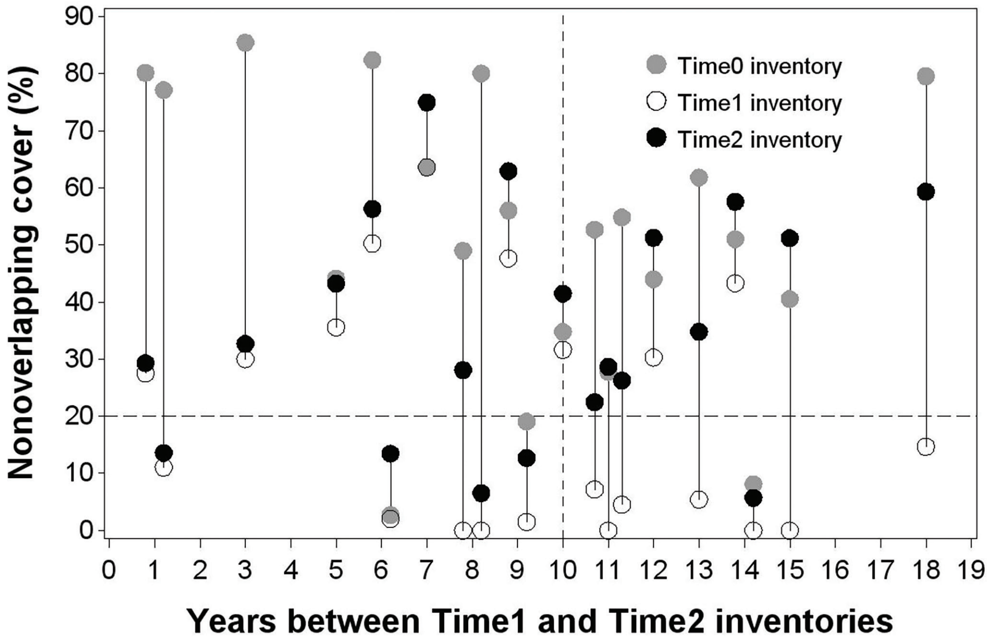

Figure 2. Canopy cover over time for 21 redeveloped lots in Falls Church, Virginia. Each vertical line connects nonoverlapping cover at Time0, the period prior to redevelopment, including trees slated for removal as well as all others on the lot; Time1, trees preserved and newly planted at the time of redevelopment; and Time2, field inventory showing canopy 1 to 18 years after redevelopment. Distance between Time0 and Time1 represents amount of canopy removed at time of redevelopment; distance between Time1 and Time2 illustrates canopy recovery over time. Dashed lines show threshold for judging whether cover at Time2 exceeds 20% (horizontal line) within 10 years (vertical line) after redevelopment (Time1). Only one lot (at 14 years) does not meet this standard and two others (at 8 and 9 years) may not quite meet it; the remaining 18 lots have or likely will exceed 20% canopy cover after 10 years.

Other Forestry Metrics

Because canopy cover does not distinguish among tree dimensions (i.e., dbh, height) to account for a given cover, we wondered if recovery of urban forests could be viewed through the conventional forestry metrics that we calculated: basal area (ba), trees per hectare (tph), and quadratic mean diameter (qmd).

Canopy cover data in Figure 3 were sorted from least to greatest decrease in cover from Time0 to Time2 and compared to similarly sorted data for ba and qmd metrics (Figure 3). Recovered basal area exceeded initial basal area on 8 of 21 lots (Figure 3B), the same number as for canopy cover (Figure 3A), but rankings differed; quadratic mean diameter, a metric of average tree size, showed only 4 of 21 lots where average tree size exceeded predevelopment tree size (Figure 3C). Only two lots (5 and 11) showed recovery exceeding predevelopment conditions for all three metrics.

Overall, Figure 3 is useful for comparing lots where a metric's Time2 value exceeded that prior to redevelopment (left of threshold) to lots not yet back to predevelopment conditions (right of threshold) and for comparing individual lots among metrics. For example, lot 7 recovery looks good from cover and basal area perspectives, but panel C reveals that when large trees are removed (i.e., qmd is greatly reduced), it takes a long time for the lot to recover that initial status. On the other hand, lot 6 recovery is relatively poor from cover and basal area perspectives but quite good in terms of preserving large trees.

Finally, basal area and canopy cover display similar patterns in Figure 3. We compared the difference between Time0 and Time2 for basal area with that for canopy cover for each lot; Pearson correlation (r = 0.918) showed close correspondence between metrics.

Objective 2: Lot-Scale Model Development

We developed a growth projection methodology for estimating future tree status that is potentially useful to urban foresters seeking to mitigate redevelopment

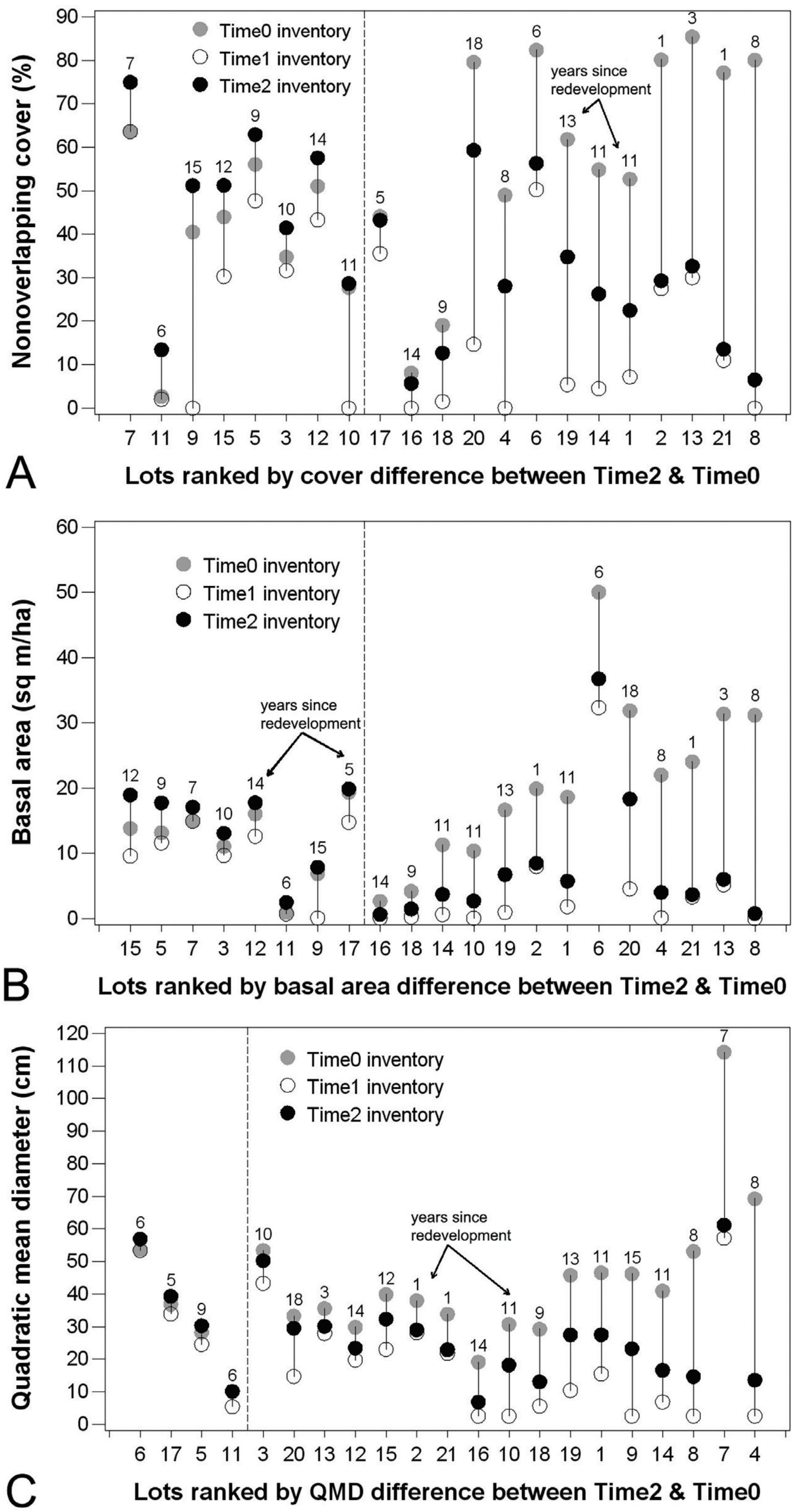

Figure 3. Comparison of 3 metrics for evaluating conditions prior to and after redevelopment for trees on 21 lots in Falls Church, Virginia. Time0 included trees slated for removal as well as all others on the lot; Time1, trees preserved and newly planted at time of redevelopment; and Time2, field inventory 1 to 18 years after redevelopment. Numbers on x-axis are lot numbers and sorted from least to greatest decrease in a metric between Time0 and Time2; in lots to the left of the dashed vertical lines (threshold), the Time2 metric has recovered and exceeds that prior to redevelopment (Time0). Panels show (A) percent nonoverlapping canopy cover, (B) basal area, and (C) quadratic mean diameter.

effects. The two-part framework described above provided a 10-year projection of canopy cover from basal area that addressed the efficacy of the city ordinance. A simplifying assumption included was that basal area growth was constant for respective planted and preserved trees over about 10 years.

The canopy cover prediction model (part 1) included 4 significant parameters (Table 2) fit from robust regression. Four average basal area growth models (part 2) were fit with robust regression; data for deciduous trees fit better than those for evergreens (Table 2).

When examining overall statistical fit of the model (by combining parts 1 and 2), the comparison of canopy cover predictions to actual data for Time2 showed more or less unbiased predictions, but the variation was large; about half the projections were more than 25% different from cover at Time2 (Figure 4). The model should be adequate for unbiased results at least for short-term projections of about 10 years in Falls Church. But we strongly caution against long-term projections, because basal-area growth of planted trees was modeled very simply and does not account for expected slower growth as trees mature. More data would have been needed to link modeled growth of planted trees to that of preserved trees in smooth transition once planted trees reached 15 to 20 years of age. Also, the model is only for growth and does not account for mortality.

We also compared modeled canopy growth of planted trees (from Time1 data) for 10 years to City of Falls Church 10-year projections of individual species crown area. The city has been using crude crown area growth tables to judge canopy cover after 10 years for planted trees (City of Falls Church 2008; pp. 6–9). The city projections were tallied ignoring any crown overlap and compared to our modeled projections. Regression showed nearly 1-to-1 correspondence (slope = 1.06 and R^2-statistic = 0.89) with a slight 2% difference (intercept = 2.3); city values were the lower (Figure 5).

DISCUSSION

We found that the City of Falls Church generally meets its desired goal of 20% canopy cover 10 years after redevelopment using current urban forest management practices, that other metrics can help more fully inform urban forest management, and that

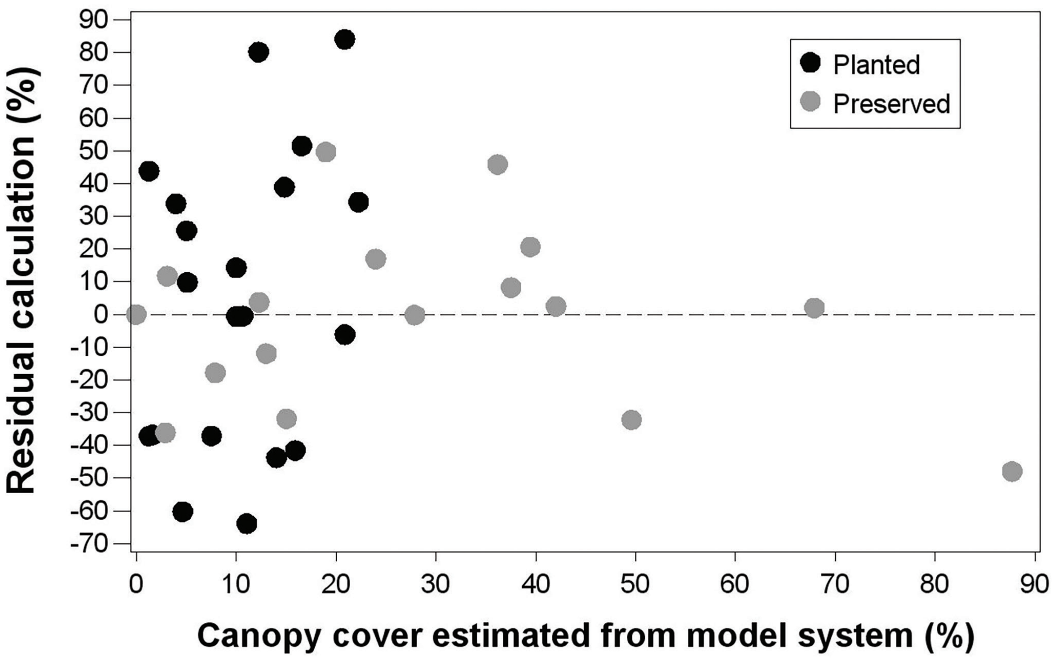

Figure 4. Canopy cover on 21 lots in Falls Church, Virginia, at Time1 (trees preserved and newly planted at time of redevelopment) was projected to Time2 (1 to 18 years after redevelopment) with a model (Table 2) and compared to actual canopy cover measured at Time2. The y-axis represents Time2 measured cover minus predicted cover divided by the average of the two covers, with the result expressed in percent. Note that negative residual differences indicate canopy cover was *overpredicted* by the model. One lot outside the range of the figure was omitted: planted cover at Time2 was 0.15% but predicted at 2.6%—over 100% overprediction.

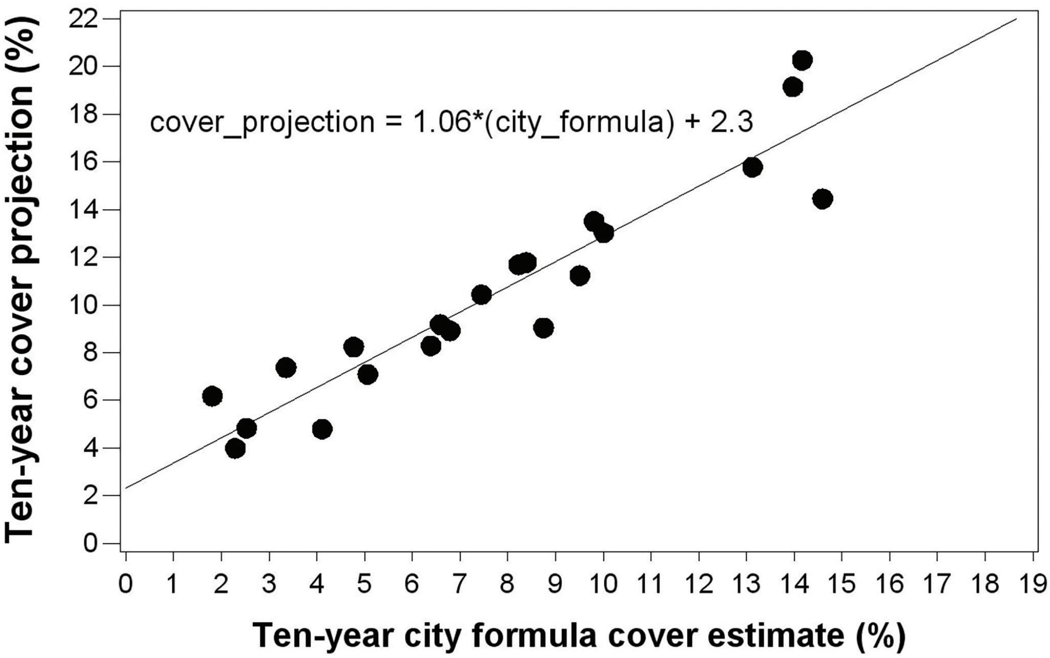

Figure 5. Comparison of canopy cover projected (cover_projection) by the model system in this study to predicted planted tree cover from City of Falls Church, Virginia, formula (city_formula). The city tables projected canopy areas of individual species listed in cover project groups from 2 to 16 m^2 in 10 years. The model predicted canopy cover on 21 lots for 10 years in Falls Church for trees newly planted at time of redevelopment (Time1).

modeling lot-scale growth from simple field measurements also shows potential for use in urban forest evaluations.

Meeting the formal 20% canopy cover requirement may fall short of the overall municipal goal of preserving and maintaining urban forests. Canopy cover was not significantly different from 20% at the time of redevelopment (after trees were removed for construction), indicating that the 20% threshold is probably too low for a compliance standard, at least for this community. Prior to redevelopment (Time0), Falls Church mean canopy cover was 52%, and lots generally had large majestic trees; canopy cover, when compared to other metrics, was shown to ignore the importance and loss of large trees. Strict reliance upon a formal rule such as "20% cover in 10 years" fits the spirit of other progressive-sounding but ineffective urban forestry practices found by Hill et al. (2010). They suggested municipalities move beyond just having a formal tree ordinance, a tree commission or board, an arborist, and so forth; instead, the key municipal entities need to interact and engage with actual results of urban forest management. Our study's findings illustrate one need to evaluate policy results: the canopy cover metric alone seems insufficient to fully describe urban forest recovery.

Canopy cover is an appealing metric because it is easily understood by the public, developers, and planners, and relatively easy to measure from aerial photographs or remote sensing data. However, it is not easy to measure in the field (Richardson and Moskal 2014), and accounting for overlap is not simple; our study required complex GIS calculations of nonoverlapping canopy cover from crown diameters measured for all trees in each lot. Furthermore, canopy cover is only two-dimensional and does not distinguish between cover of small and large trees.

On the other hand, basal area and quadratic mean diameter (qmd) are metrics that are easily calculated from only tree diameter measurements and that can be used to monitor and manage trees for the larger sizes (large dbh, tall height, and wide crown) that maximize benefits to urban forest environmental services (McPherson et al. 2006; Alliance for Community Trees 2011; Ko et al. 2015). For example, in our study the qmd metric showed that although canopy cover might recover rapidly (from planting many small trees), recovery to average tree size prior to development can take much longer; for only 4 of 21 lots did average tree size exceed predevelopment tree size.

Modeling cover as a function of basal area is a promising strategy. Through our modeling effort, we showed the potential to manage urban forests "on the ground" using traditional forestry metrics based on dbh measurement, and yet still relate results to canopy cover when needed for code ordinances or common understanding. Our growth model corroborated the current City of Falls Church practice of basing new tree planting upon 10-year tree-scale canopy cover. Data from the 21 lots sampled were insufficient to fully develop a canopy growth projection system for widespread use, particularly for growth projections exceeding 10 years; the time-consuming task of securing access to private residential yards hampers collection of adequate data for studies such as this (Roman et al. 2014; Nguyen et al. 2017). Nevertheless, results were promising, and we feel strongly that arborists and urban foresters should use every opportunity to start measuring urban forest tree diameters accurately and on an area basis (e.g., lot area or smaller plot size where appropriate) in anticipation of more widespread use of basal area and quadratic mean diameter metrics—in other words, basal–area–based management. These professionals should take the lead in ensuring that measurements are accurate and precise (to nearest 0.50 cm or 0.1 inch), regardless of immediate needs or contract specifications, so that solid management data will be available.

As practitioners know, urban forestry affects the lives and health of the majority of the world population; most of us now live in cities (United Nations 2014). It is also a relatively new field (Miller et al. 2015). Our initial findings show that urban forestry research needs are great, as are the opportunities to improve practices in the field and support the forests in our communities. Because we found no similar residential urban forest inventory studies, we used a simple sampling scheme and borrowed heavily from conventional forest inventory techniques. Perhaps others can now improve upon our work to strengthen scientific foundations for municipal forest inventories and monitoring of residential city property. We applaud the National Urban and Community Forestry Advisory Council for recognizing the need for more urban forestry research (NUCFAC 2015). We think that tree ordinances and other community practices aimed to improve urban forests need to be backed by solid science in order to attain maximum effectiveness and avoid becoming mere quick fixes.

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The authors reported no conflicts of interest.

Résumé. Les administrations locales ont émis des dispositions réglementaires destinées à maintenir et à accroître le précieux couvert forestier urbain. La ville de Falls Church, Virginie, USA, requiert, au moment de tout redéveloppement résidentiel, de maintenir ou de planter suffisamment d'arbres afin d'obtenir un couvert arborescent de 20% au terme des dix années suivantes. Afin de déterminer si cet objectif est atteint, 21 lots résidentiels de Falls Church, redéveloppés entre 1994 et 2011 aux fins du remplacement de maisons existantes par des maisons plus grandes, furent étudiés. Les données initiales d'inventaire et de mesures des arbres préalablement au redéveloppement avaient été enregistrées sur les plans proposés pour ce redéveloppement. Un relevé de terrain permit de remesurer les arbres préservés ainsi que ceux plantés depuis et nous modélisâmes la croissance du couvert des arbres à partir d'un modèle périodique de croissance du diamètre des arbres et d'un autre modèle associant le diamètre du tronc à celui de la cime. Une analyse géospatiale fut utilisée afin de calculer le couvert arborescent non chevauchant à l'intérieur des lots à partir des mesures de diamètre de la cime et/ou des prédictions du modèle. Nous constatâmes que la ville de Falls Church rencontrait généralement son objectif de 20% du couvert arborescent, mais que la seule donnée du couvert forestier était insuffisante pour décrire complètement le rétablissement de la forêt urbaine. Bien que le couvert arborescent puisse récupérer rapidement suite à la plantation de plusieurs petits arbres, le rendement attendu d'arbres de grande dimension maximisant les services écosystémiques nécessitait beaucoup plus de temps. Notre modélisation de la croissance à l'échelle des lots suite aux relevés de terrain démontra le potentiel de gérer les forêts en utilisant les données traditionnelles basées sur le diamètre mais dont les résultats pouvaient être corrélés lorsque le couvert forestier était recherché. Ces données sur les peuplements forestiers, basées sur les surfaces terrières et le nombre d'arbres par hectare, pouvaient être pris en compte pour les modifications des dimensions non-visibles des arbres au-moment de la mesure du couvert arborescent.

Zusammenfassung. Lokale Verwaltungen haben Regelwerke entwickelt, die wertvollen urbanen Baumbestand erhalten und vergrößern. Die Stadt Falls Church, Virginia, USA, fordert bei jeder Neuentwicklung von Siedlungsräumen entweder genug Bäume zu pflanzen oder zu erhalten, um innerhalb von 10 Jahren eine Bedeckung von 20 % zu erzielen. Für die Untersuchung, ob dieses Ziel erreicht wird, studierten wir 21 Siedlungsbereiche in Falls Church, die zwischen 19994 und 2011 neu gestaltet wurden, wo die existierenden Häuser durch größere ersetzt wurden. Erste Baumkataster und Messungen vor der Umgestaltung wurden in die Entwicklungspläne aufgenommen. In einer Bodenerfassung wurden die erhaltenen und gepflanzten Bäume neu vermessen und das Kronenwachstum von einem periodischen Baumdurchmesserwachstumsmodell beispielhaft übernommen und mit einem Modell zur Beziehung zwischen Baum und Kronendurchmesser verbunden. Eine räumliche Analyse wurde verwandt, um die nicht überlappenden Kronenbedeckungen innerhalb der Siedlungsbereiche aus den Kronendurchmessermessungen und/oder den Modellvorhersagen zu kalkulieren. Wir fanden heraus, dass die Stadt Falls Church generell ihr Ziel von 20 % erreicht, aber dass die Kronenbedeckung allein nicht ausreicht, um die Erholung der urbanen Forste zu beschreiben. Obwohl sich die Kronenbedeckung durch die Pflanzung kleinerer Bäume schnell erholen könnte, wird das Heranwachsen zu großen Baumgrößen, die die ökologischen Leistungen maximieren, viel länger dauern. Unser Modell von flächenbezogenem Wachstum aus Feldmessungen zeigte das Potential zur Verwaltung von Waldflächen unter der Verwendung traditioneller auf Durchmesser basierender Forstmesswerte, die die Ergebnisse zur Kronenbedeckung wenn erforderlich relativieren würden. Diese Forstmesswerte—basierend auf basaler Fläche und Baum pro Hektar können für die Baumgrößenveränderungen in Bezug zur Kronenbedeckung hinzugezogen werden.

Resumen. Los gobiernos locales han creado regulaciones destinadas a mantener y aumentar la valiosa cubierta de árboles urbanos. La ciudad de Falls Church, Virginia, EE. UU., requiere que cada remodelación residencial retenga o plante suficientes árboles para una cobertura del dosel en un plazo de diez años. Para evaluar si se ha cumplido este objetivo, estudiamos 21 lotes residenciales de Falls Church reconstruidos entre 1994 y 2011, donde las casas existentes habían sido reemplazadas por otras más grandes. Los inventarios y mediciones iniciales de los árboles antes de la reurbanización se registraron en los planes de reurbanización. Volvimos a medir los árboles preservados y plantados en un estudio de suelo y modelamos el crecimiento de la copa de los árboles a partir de un modelo de crecimiento periódico del diámetro del árbol vinculado a un modelo que relaciona los diámetros de los árboles y las copas. El análisis geoespacial se usó para calcular la cobertura del dosel sin solapamiento dentro de los lotes a partir de mediciones del diámetro de la corona y / o predicciones del modelo. Descubrimos que la ciudad de Falls Church generalmente cumplió con su objetivo de cobertura del dosel del 20%, pero que la métrica de la cubierta del dosel por sí sola es insuficiente para describir completamente la recuperación del bosque urbano. Aunque la cubierta del dosel puede recuperarse rápidamente a partir de la plantación de muchos árboles pequeños, la recuperación a los árboles más grandes que maximizan los servicios del ecosistema puede llevar mucho más tiempo. Nuestro modelo de crecimiento a escala de lote a partir de mediciones de campo mostró el potencial para gestionar los bosques utilizando métricas forestales tradicionales basadas en el diámetro que relacionarían los resultados con la cubierta del dosel cuando sea necesario. Estas métricas de masas forestales, basadas en el área basal y los árboles por hectárea, pueden dar cuenta de los cambios en el tamaño de los árboles enmascarados por la métrica de la cubierta del dosel.